MEETING THE UNIVERSE HALFWAY

quantum physics and the **entanglement** of matter and meaning

KAREN BARAD

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FOR MIKAELA

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PREFACE AND ACKNOWLEDGMENTS

This book is about entanglements. To be entangled is not simply to be intertwined with another, as in the joining of separate entities, but to lack an independent, self-contained existence. Existence is not an individual affair. Individuals do not preexist their interactions; rather, individuals emerge through and as part of their entangled intra-relating. Which is not to say that emergence happens once and for all, as an event or as a process that takes place according to some external measure of space and of time, but rather that time and space, like matter and meaning, come into existence, are iteratively reconfigured through each intra-action, thereby making it impossible to differentiate in any absolute sense between creation and renewal, beginning and returning, continuity and discontinuity, here and there, past and future.

What does it mean therefore to write an acknowledgment, to acknowledge or recognize contributors and contributions that help make something happen? Writing an acknowledgment cannot be a matter of simply committing to paper key moments and key individuals identified and selected from various scans through the book of memories written into and preserved in the mind of an author. Memory does not reside in the folds of individual brains; rather, memory is the enfoldings of space-time-matter written into the universe, or better, the enfolded articulations of the universe in its mattering. Memory is not a record of a fixed past that can ever be fully or simply erased, written over, or recovered (that is, taken away or taken back into one's possession, as if it were a thing that can be owned). And remembering is not a replay of a string of moments, but an enlivening and reconfiguring of past and future that is larger than any individual. Remembering and re-cognizing do not take care of, or satisfy, or in any other way reduce one's responsibilities; rather, like all intra-actions, they extend the entanglements and responsibilities of which one is a part. The past is never finished. It cannot be wrapped up like a package, or a scrapbook, or an acknowledgment; we never leave it and it never leaves us behind.

So this acknowledgment does not follow (and does not not follow) the tradition of an author reminiscing about the long process of writing a book and naming supporters along the way that made the journey possible. There is no singular point in time that marks the beginning of this book, nor is there an "I" who saw the project through from beginning to end, nor is writing a process that any individual "I" or even group of "I's" can claim credit for. In an important sense, it is not so much that I have written this book, as that it has written me. Or rather, "we" have "intra-actively" written each other ("intra-actively" rather than the usual "interactively" since writing is not a unidirectional practice of creation that flows from author to page, but rather the practice of writing is an iterative and mutually constitutive working out, and reworking, of "book" and "author"). Which is not to deny my own agency (as it were) but to call into question the nature of agency and its presumed localization within individuals (whether human or nonhuman). Furthermore, entanglements are not isolated binary coproductions as the example of an author-book pair might suggest. Friends, colleagues, students, and family members, multiple academic institutions, departments, and disciplines, the forests, streams, and beaches of the eastern and western coasts, the awesome peace and clarity of early morning hours, and much more were a part of what helped constitute both this "book" and its "author."

I smile at the thought of imagining my mother reading this and thinking that I have made things unnecessarily complicated once again; that I have been thinking too much, and that anyone else would have just gotten to the point and said their thank-you's in a manner that all the people who have helped along the way could understand. On the one hand, she's right of course: what good is there in offering recognition that can't be recognized? But it is precisely because of the passionate yearning for justice enfolded into the core of my being—a passion and a yearning inherited from and actively nurtured by my mother—that I cannot simply say what needs to be said (as if that were a given) and be done with it. Justice, which entails acknowledgment, recognition, and loving attention, is not a state that can be achieved once and for all. There are no solutions; there is only the ongoing practice of being open and alive to each meeting, each intra-action, so that we might use our ability to respond, our responsibility, to help awaken, to breathe life into ever new possibilities for living justly. The world and its possibilities for becoming are remade in each meeting. How then shall we understand our role in helping constitute who and what come to matter? How to understand what is entailed in the practice of meeting that might help keep the possibility of justice alive in a world that seems to thrive on death? How to be alive to each being's suffering, including those who have died and those not yet born? How to disrupt patterns of thinking that see the past as finished and the future as not ours or only ours? How to understand the matter of mattering, the nature of matter, space, and time? These questions and concerns are not a luxury made of esoteric musings. Mattering and its possibilities and impossibilities for justice are integral parts of the universe in its becoming; an invitation to live justly is written into the very matter of being. How to respond to that invitation is as much a question about the nature of response and responsibility as it about the nature of matter. The yearning for justice, a yearning larger than any individual or sets of individuals, is the driving force behind this work, which is therefore necessarily about our connections and responsibilities to one another—that is, entanglements.

I have been fortunate beyond measure to be entangled with many remarkable beings who have sustained and nourished me, and who have offered gifts of friendship, kindness, warmth, humor, love, encouragement, inspiration, patience, the joy of intellectual engagement, invaluable feedback, vigorous challenge, attentiveness to detail, and love of ideas. My gratitude encompasses more beings than can be listed on any number of sheets of paper. Lists simply cannot do justice to entanglements. I can only hope that anyone (from my past or future, known to me or perhaps not) who looks for her or his name in this acknowledgment and is disappointed not to find it will understand that she or he is nonetheless written into the living and changing phenomenon that rightly deserves the name "book," which is surely not the simple object one can hold in one's hands.

First of all, I want to thank my students at Barnard College, Pomona College, Rutgers University, Mount Holyoke College, and the University of California at Santa Cruz. I have learned more from you and you have given more to me than you'll ever know.

I am indebted to Elisabeth (Jay) Friedman and Temma Kaplan for accompanying me on those early forays into newly charted territories. Who knew? In creating an extraordinary history of physics laboratory at Barnard College, physicist Samuel Devons (who was a student of Ernest Rutherford) unknowingly opened up a new world for me. Teaching in that laboratory, preparing experiments, and negotiating with magnificent pieces of old equipment, I began to develop an appreciation for the physicality of apparatuses and the ideas they embody. No part of my formal training in (theoretical) physics had given me any sense of that, although my ongoing independent and self-directed studies of Niels Bohr's philosophy-physics no doubt helped prepare me to take in this particularly Bohrian insight. Some of the greatest debts we have are to those who live in different times and spaces (at least according to the wholly inadequate conception that there are such external measures of absolute difference); although we never met in the flesh, I would be seriously remiss if I did not thank Niels Bohr, who has been a most wonderful interlocutor over the years.

I have been extraordinarily fortunate to receive gifts of encouragement and intellectual and spiritual nourishment from friends and colleagues along the way. They include Alice Adams, Bettina Aptheker, Mario Biagioli, Rosi Braidotti, Judith Butler, Lorraine Code, Giovana Di Chiro, Camilla Funck Ellehave, Leela Fernandes, Nancy Flam, Michael Flower, Alicia Gaspar de Alba, Ruth Wilson Gilmore, BJ Goldberg, Deena Gonzalez, Alice Fulton, Jacob Hale, Sandra Harding, Emily Honig, Sue Houchins, David Hoy, Jocelyn Hoy, Marilyn Ivy, Evelyn Fox Keller, Lori Klein, Martin Krieger, Jay Ladin, Mark Lance, Lynn LeRose, Janna Levin, Laura Liu, Nina Lykke, Paula Marcus, Linda Martín-Alcoff, Lynn Hankinson Nelson, Rupal Oza, Frances Pohl, Elizabeth Potter, Ravi Rajan, Jenny Reardon, Irene Reti, Jeanne Rosen, Sue Rosser, Paul Roth, Jennifer Rycenga, Joan Saperstan, Victor Silverman, Caridad Souza, Banu Subramaniam, Lucy Suchman, Charis Thompson, Sharon Traweek, Sheila Weinberg, Barbara Whitten, Elizabeth Wilson, and Alison Wylie.

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I am immeasurably grateful to my parents, Harold and Edith Barad, for believing in me, no matter what. My mother's unfaltering faith in the goodness of all people and her insistence on seeing the best in each person is a rarity in this world and an inspiration. My heartfelt thanks to my father for teaching me to throw a baseball and sink a basket better than any boy in the neighborhood; the days we spent playing ball together were founding feminist moments in my life that taught me remarkably useful lessons and skills that I have carried with me. My first really important insights about the nature of measurement and value came from my parents; I feel very fortunate indeed to have been raised with working-class values, which refuse to measure the value or worth of a person by their profession, accomplishments, education, wealth, or worldliness.

Roanne Wilson gave generously of herself throughout the writing of this book, offering warm meals, companionship, love, flexibility in co-parenting, abundant support, and hot chocolate at just the right moments. There is no "thank you" that can speak to all the tangibles and intangibles that she has given me.

My daughter, Mikaela, has in many ways been my closest collaborator. The way she meets the world each day with an open and loving heart-mind has taught me a great deal. Her insatiable sense of curiosity, unabated ability to experience pure joy in learning, wide-open sense of caring for other beings, and loving attentiveness to life (taking in the tiniest details and textures of the world, which she re-creates through poetry, drawings, paintings, sculpture, stories, dance, and song) are key ingredients to making possible futures worth remembering. This book is dedicated to her.

RADHKVV

MEETING THE UNIVERSE HALFWAY

PART I

ENTANGLED BEGINNINGS

The Science and Ethics of Mattering

Matter and meaning are not separate elements. They are inextricably fused together, and no event, no matter how energetic, can tear them asunder. Even atoms, whose very name, ατομοσ (*atomos*), means "indivisible" or "uncuttable," can be broken apart. But matter and meaning cannot be dissociated, not by chemical processing, or centrifuge, or nuclear blast. Mattering is simultaneously a matter of substance and significance, most evidently perhaps when it is the nature of matter that is in question, when the smallest parts of matter are found to be capable of exploding deeply entrenched ideas and large cities. Perhaps this is why contemporary physics makes the inescapable entanglement of matters of being, knowing, and doing, of ontology, epistemology, and ethics, of fact and value, so tangible, so poignant.

SETTING THE SCENE

In September 1941, when Nazi empire building had reached its pinnacle, the German physicist Werner Heisenberg paid a visit to his mentor Niels Bohr in Nazi-occupied Denmark. Bohr, who was of Jewish ancestry, was head of the world-renowned physics institute in Copenhagen that bears his name. Heisenberg, Bohr's protégé and a leading physicist in his own right, was at that time head of the German effort to produce an atomic bomb. Filled with nationalist pride for his homeland, Heisenberg decided to stay in Germany despite offers from abroad, but by all accounts he was not a Nazi or a Nazi sympathizer. Bohr and Heisenberg were two of the great leaders of the quantum revolution in physics. Their respective interpretations of quantum physics—complementarity and uncertainty—constitute the nucleus of the so-called Copenhagen interpretation of quantum mechanics. The two Nobel laureates had a special bond between them—a relationship described as that between father (Bohr) and son (Heisenberg)—that was broken apart by the events of this inauspicious visit. Although the details of what transpired during their fateful exchange in the autumn of 1941 are still a matter of controversy, it is clear that matters of the gravest consequences, including the prospect of a German atomic bomb, were discussed.[1]

Why did Heisenberg come to Copenhagen? What was he hoping to talk with Bohr about? What were his intentions? Did Heisenberg hope to find out what Bohr knew about the Allied bomb project? Did he come to warn Bohr about the German project and reassure him that he was doing everything in his power to stall it? Did he want to see if he could convince Bohr to take advantage of their shared status as authorities on atomic physics to convince both sides to abandon their respective projects to build atomic weapons? Did he hope to gain some important insight from his mentor about physics or ethics or the relationship between the two?

This question—why Heisenberg went to see Bohr in 1941—is the focal point of a recent Tony Award–winning play that considers the controversy surrounding this fateful meeting. The play doesn't resolve the controversy; on the contrary, the play itself has gotten caught up in its very orbit. In Michael Frayn's play *Copenhagen*, the ghosts of Bohr, Heisenberg, and Bohr's wife, Margrethe, meet at the old Bohr residence to try to reconcile the events of that fateful autumn day. As if working out the details of a problem in atomic physics, Bohr, Heisenberg, and Margrethe make three attempts to calculate Heisenberg's intentions, by enacting and at times stopping to reflect on three possible scenarios of what might have occurred. Each attempt to resolve the uncertainty is foiled. But that is precisely the point Frayn wishes to make: drawing an analogy with Heisenberg's uncertainty principle, Frayn suggests that the question of why Heisenberg came to Copenhagen in 1941 does not remain unresolved for any practical reason, such as some insufficiency in the historical record that can be straightened out with newfound evidence or some new clarifying insight, but rather is unresolvable *in principle* because uncertainty is an inherent feature of human thinking, and when all is said and done, no one, not even Heisenberg, understands why he came to Copenhagen.

Frayn's uncertainty principle—the one that says that "we can [in theory] never know everything about human thinking"—is not an actual consequence of Heisenberg's uncertainty principle but an invention of the playwright, created purely on the basis of analogy. Frayn is not applying the Heisenberg uncertainty principle—which concerns the limits to our knowledge of the behavior of physical objects, like atoms or electrons—to the problem of what it is possible to know about human behavior; he is simply drawing a parallel. Using this analogy, Frayn moves rapidly from the realm of epistemology (questions about the nature of knowledge) to the domain of morality (questions about values), from the uncertainty of intentionality to the undecidability of moral issues. On the basis of his own uncertainty principle, he reasons, or perhaps moralizes, that because we can never really

know why anyone does what he or she does, moral judgments lose their foundation. We'll never know whether Heisenberg was actively trying to build an atom bomb for Germany or whether he purposely foiled these efforts to prevent Hitler from getting his hands on new weapons of mass destruction. We are placed face-to-face with a question of profound moral significance where nothing less than the fate of humanity was at stake, and uncertainty foils our efforts to assign responsibility—uncertainty saves Heisenberg's tormented soul from the judgments of history. The play thereby raises more specters than it puts to rest.

Copenhagen is an engaging, clever, and beautifully written play. It has all the allure of a romance with its bold display of explicit intimacy between science and politics, peppered with the right amount of controversy. It also has its share of critics. While many critics have taken issue with important historical inaccuracies that haunt the play, my focus is on Frayn's portrayal of quantum physics and its philosophical implications, a portrayal, I will argue, that is fraught with difficulties.

Frayn's play serves as a useful counterpoint to what I hope to accomplish in this book. On the surface, the subject matter may appear similar. Questions of science, politics, ethics, and epistemology are among the key concerns taken up in this book. Indeed, quantum physics and its philosophical implications and differences in the approaches of Bohr and Heisenberg figure centrally here as well. But this is where the similarity ends. We diverge in purpose, approach, methodology, genre, style, audience, backgrounds, interests, values, level of accountability to empirical facts, standards of rigor, forms of analysis, modes of argumentation, and conclusions. Crucially, we also sharply diverge in our philosophical starting points and the depth of our respective engagements with the physics and the philosophical issues.

In an important sense, Frayn's viewpoint is more familiar and fits more easily with common-sense notions about the nature of knowing and being than the view I will present here. Frayn presents his audience with a set of binaries—the social and the natural, the macroscopic and the microscopic, the laws of man and the laws of nature, internal states of consciousness and external states of being, intentionality and history, ethics and epistemology, discourse and materiality—and his approach to relating the two sets is to draw analogies across the gap. He also presupposes a metaphysics of individualism for both the micro and macro scales: humans, like atoms, are assumed to be discrete individuals with inherent characteristics (such as intelligence, temperament, and intentional states of mind). And at times he freely mixes issues of being and knowing, ontology and epistemology, as if they were interchangeable isotopes in a chemical brew.

What, if anything, does quantum physics tell us about the nature of scientific practice and its relationship to ethics? Before this question can be approached, two prior issues must be addressed. First of all, there is an important sense in which the question is not well defined. The interpretative issues in quantum physics (i.e., questions related to what the theory means and how to understand its relationship to the world) are far from settled. When questions about the philosophical implications of quantum physics arise, no definitive answers can be given in the absence of the specification of a particular interpretation. Moreover, public fascination with the subject has been met with a plethora of popular accounts that have sacrificed rigor for the sake of accessibility, entertainment, and, if one is honest, the chance to garner the authority of science to underwrite one's favorite view.[2] As a result the public is primed to accept any old counterintuitive claim as speaking the truth about quantum theory. These factors, taken together, pose serious difficulties for anyone trying to make sense of, let alone answer, this potentially important question. Clearly any serious consideration of this question must begin by disambiguating legitimate issues from fancy and taking a clear stand with respect to the interpretative issues.

Public fascination with quantum physics is probably due in large part to several different factors, including the counterintuitive challenges it poses to the modernist worldview, the fame of the leading personalities who developed and contested the theory (Einstein not least among them), and the profound and world-changing applications quantum physics has wrought (often symbolized in the public imagination, fairly or unfairly, by the development of the atomic bomb). But can it be this factor alone—this public hunger to know about quantum physics—that accounts for the plethora of incorrect, misleading, and otherwise inadequate accounts? What is it about the subject matter of quantum physics that it inspires all the right questions, brings the key issues to the fore, promotes open-mindedness and inquisitiveness, and yet when we gather round to learn its wisdom, the response that we get almost inevitably seems to miss the mark? One is *almost* tempted to hypothesize an uncertainty relation of sorts that represents a necessary trade-off between relevance and understanding. But this is precisely the kind of analogical thinking that has so often produced unsatisfactory understandings of the relevant issues.

We cannot hope to do justice to this important question—the implications of quantum physics for understanding the relationship between science and ethics—on the basis of mere analogies. That's one important lesson we should understand from the plethora of failed attempts. Frayn's *Copenhagen* is a case in point. In this sense the play can be used as an important teaching tool. In what follows, I examine the play in some detail to draw some important contrasts and to help set the stage for introducing some of the main themes of this book. This interlude provides a dramatic introduction to some of the relevant historical background, main characters, and key ideas and enables me to highlight some of the important ways in which my approach differs from the more common analogical approaches.

"Does one as a physicist have the moral right to work on the practical exploitation of atomic energy?"[3] Heisenberg's haunting question to Bohr hangs in the air throughout *Copenhagen*. But for its playwright, Michael Frayn, this moral question is a side issue. The one that really interests him is the metaethical question of how it is possible to make moral judgments at all. Frayn puts it this way: "The moral issues always finally depend on the epistemological one, on the judgment of other people's motives, because if you can't have any knowledge of other people's motives, it's very difficult to come to any objective moral judgment of their behavior."[4] But how does this dilemma arise? Why can't we have any knowledge of other people's motives and intentions? According to Frayn, the root of the dilemma derives from the analogy he wants to draw with Heisenberg's uncertainty principle. The Heisenberg uncertainty principle says that there is a necessary limit to what we can simultaneously know about certain pairs of physical quantities, such as the position and momentum of a particle. (The momentum of a particle is related to its velocity; in particular, momentum is mass times velocity.) Frayn suggests that by way of analogy there is a necessary limit to what we can know about mental states (such as thoughts, intentions, and motivations), including our own. But if the goal is to set up an uncertainty principle for people in analogy with the famous one that Heisenberg proposes for particles, and one is committed to doing so with some care, then it does *not* follow that "we can't have *any* knowledge of other people's motives."

Let's look more closely at what Heisenberg's principle says. Heisenberg does not say that we can't have any knowledge about a particle's position and momentum; rather, he specifies a trade-off between how well we can know both quantities at once: the more we know about a particle's position, the less we know about its momentum, and vice versa.[5] So if, as Frayn suggests, he is interested in constructing an analogous principle for people that specifies a trade-off between a subject's actions and the subject's motivations behind those actions, it would have to say something more along the lines of: we can't have *full* knowledge of people's motives and know something about their actions that enact those motives; that is, we can't be *fully* certain about both a person's actions and what motivated those actions. (Which is not to say that I endorse such a principle. I am simply trying to tidy up the analogy Frayn wants to make.) But the fact that knowledge of motivations is not *prohibited*, but rather *limited*, has enormously important consequences for thinking about the question of moral judgment. Frayn argues that since there is no way *in principle* to get around the limits of our knowledge, and we are therefore forever blocked from having *any* knowledge about someone's motives, it is not possible to make any objective moral judgments. However, as we just saw, a more careful way of drawing the analogy does not in fact undermine any and all considerations of moral issues based on knowledge of the motivations behind a subject's actions, as long as those considerations do not require full and complete knowledge but can instead be based on partial understandings.

Now, Frayn is the first to admit that the analogy that he draws is not an exact parallel, but his admission has nothing to do with the crucial fault in his analogical reasoning that we just discussed. Rather, Frayn's concession is of a different sort: he readily acknowledges that he is not making an *argument* for the limits of moral judgment on the basis of quantum physics. But he does see his play as a means of exploring a parallel epistemic limit for discerning the content of mental states (like thoughts, motives, and intentions). Hence his overstatement of the principled limitation poses a fundamental difficulty that goes to the core issue of the play. But rather than stop here, it is instructive to continue our considerations of Frayn's analogical methodology. Before we examine how Frayn exploits this parallel in the play, it's important to understand what is at stake in the way he frames the issues. (Another specter haunts the play: questions of the playwright's motivations.)

The stakes are these. The controversy about the matter of Heisenberg's intentions in visiting Bohr in Nazi-occupied Copenhagen in 1941 has never been settled. Indeed, the question about why Heisenberg went to visit Bohr during the war is a pivotal clue in a much larger puzzle that history yearns to (re)solve: What role did Heisenberg play as a leading German scientist and head of the Nazi bomb project during World War II? Did Heisenberg, as he claimed after the war, do his best to foil the German bomb project? Or was the actual stumbling block that undermined the German project the fact that Heisenberg had failed to get the physics right, a conclusion drawn by the majority of the physics community? Frayn is clearly sympathetic to Heisenberg's postwar rendering. And Frayn also doesn't hide the fact that his uncertainty principle for psychological states of mind is a means of attempting to get history to back off from issuing any harsh judgments against Heisenberg. "I find it very difficult to judge people who lived in totalitarian societies," Frayn says. "You can admire people who acted heroically, but you can't expect people to behave that way."[6]

It's important to note that the play itself generated a considerable amount of controversy, especially following its opening in the United States. Its enthusiastic reception in London notwithstanding, American scientists and historians of science have criticized the play for its gross historical inaccuracies and its far-too-sympathetic portrayal of Heisenberg. Frayn acknowledges that Thomas Powers's Pulitzer Prize–winning book *Heisenberg's War: The Secret History of the German Bomb* (1993) was the inspiration for his play. Inspiration is one thing, but when a discredited account forms the primary basis for drawing the outlines and details of a dramatization of an important historical encounter, does the artist not have some obligation to history? What are the moral obligations and responsibilities of the artist? Questions of this nature have been asked of Frayn. But even with the emergence of new historical evidence that flies in the face of Frayn's reconstruction, he remains resolutely unrepentant. In his responses to his critics, he insists that he doesn't feel any obligation to hold himself responsible to the historical facts. Perhaps we shouldn't be surprised, since he claims to have offered a principled argument to absolve Heisenberg from any responsibility to history. (Perhaps Heisenberg does indeed deserve absolution, but Frayn's argument is that we have no ground to make such a determination.)

Significantly, the journalist Thomas Powers's rendition is based on the discredited thesis of the Swiss-German journalist Robert Jungk. Initially published in German, Jungk's reconstruction of the historical events, *Brighter than a Thousand Suns* (German edition, 1956; English edition, 1958), exculpates the German scientists for their involvement in the war effort, Heisenberg foremost among them, and argues that they were secretly engaged in resistance efforts against Hitler. In Powers's book we find this myth of heroic resistance expanded into a highly embellished "shadow history" of the German atomic bomb project. Significantly, Robert Jungk has publicly repudiated his own thesis. For his part, Jungk admits to having been far too impressed with the personalities involved. Jungk takes his inspiration from a letter Heisenberg sent to him after the war detailing his recollection of the famous 1941 meeting with Bohr. Jungk includes a copy of the letter in his book. He notes that "if one could interpret the content of [the] conversation [between Bohr and Heisenberg] in psychological terms, it would depend on very fine nuances indeed."[7]

Frayn was clearly impressed by the possibility of considering the "very fine nuances" in psychological terms, but Bohr was not. Bohr was enraged by Heisenberg's recasting of the story. Upon encountering the letter in Jungk's book, Bohr drafted a letter to Heisenberg denouncing his misleading account. But Bohr never sent the letter. Following his death in 1962, the Bohr family discovered several drafts of the letter and deposited them with the Niels Bohr Archive in Copenhagen with instructions to have them sealed until 2012, fifty years after Bohr's death. Historians could only speculate about Bohr's version of the encounter. But then, in 2002, the Bohr family agreed to the early release of all documents pertaining to the 1941 visit, including different versions of Bohr's unsent letter to Heisenberg.[8] The early release was precipitated by public interest in the controversy generated by Frayn's *Copenhagen*.

What do the documents reveal? In his response to Heisenberg, Bohr makes it clear that he was shocked and dismayed by the news Heisenberg brought to Copenhagen in 1941 "that Germany was participating vigorously in a race to be the first with atomic weapons." Bohr writes to Heisenberg:

> You . . . expressed your definite conviction that Germany would win and that it was therefore quite foolish for us to maintain the hope of a different outcome of the war and to be reticent as regards all German offers of cooperation. I also remember quite clearly our conversation in my room at the Institute, where in vague terms you spoke in a manner that could only give me the firm impression that, under your leadership, everything was being done in Germany to develop atomic weapons and that you said that there was no need to talk about details since you were completely familiar with them and had spent the past two years working more or less exclusively on such preparations. I listened to this without speaking since [a] great matter for mankind was at issue in which, despite our personal friendship, we had to be regarded as representatives of two sides engaged in mortal combat. (Niels Bohr Archive)

And in a draft written in 1962, the year of Bohr's death, Bohr tells Heisenberg it is "quite incomprehensible to me that you should think that you hinted to me that the German physicists would do all they could to prevent such an application of atomic science," in direct contradiction of the story Heisenberg tells to Jungk, which is later embellished by Powers.

How does Frayn react to this revelation? He remains steadfast in the face of this crucial addition to the historical record. Frayn has indicated that the release of these important historical documents has had little effect on his thinking about the relevant issues and would not affect any future editions of the play. He admits only one inaccuracy: that he portrays Bohr as having

forgiven Heisenberg too readily.[9] This dismissive stance toward history is completely consistent with Frayn's privileging of psychological ("internal") states over historical ("external") facts throughout the play, a point, as we will see, that reaches a crescendo in the play's final scene. For Frayn, no historical fact can trump psychological uncertainty; we are not accountable to history, *in principle*.

With this background, let's return to the play and see how Frayn handles the metaethical dilemma he poses. Miming Bohr's propensity for working through physics problems by writing multiple drafts of a paper, Frayn offers his audience three possible scenarios—three complementary "drafts" exploring different points of view—for what occurred during the conversation between Bohr and Heisenberg on the occasion of Heisenberg's visit to Bohr in 1941. The first draft is largely a presentation of Heisenberg's point of view, replete with embellishments compliments of Jungk and Powers. Bohr's wife, Margrethe, is a major figure in the second draft. She represents the informed majority public opinion, consonant with the majority view of the physics community, which rejects Heisenberg's claim to have been consciously working to thwart the German bomb project, and largely sees the failure of the project to be the fortunate result of Heisenberg's failure to appreciate the relatively small amount of fissionable material needed to make a bomb. The third draft is where Frayn's philosophical interests in the play come to the fore.

There are two important elements to the third draft, which delivers the play's conclusions: one brings the analogy between the unknowability of physical states and psychological states to its climax, and the other explores the limits of the analogy. This final draft highlights Frayn's point that we are prohibited, in principle, from knowing our own thoughts, motives, and intentions. The only possibility we have of catching a glimpse of ourselves is through the eyes of another.

> *Heisenberg*: And yet how much more difficult still it is to catch the slightest glimpse of what's behind one's eyes. Here I am at the centre of the universe, and yet all I can see are two smiles that don't belong to me. . . .
> *Bohr*: I glance at Margrethe, and for a moment I see what she can see and I can't—myself, and the smile vanishing from my face as poor Heisenberg blunders on.
> *Heisenberg*: I look at the two of them looking at me, and for a moment I see the third person in the room as clearly as I see them. Their importunate guest, stumbling from one crass and unwelcome thoughtfulness to the next.

Bohr: I look at him looking at me, anxiously, pleadingly, urging me back to the old days, and I see what he sees. And yes—now it comes, now it comes—there's someone missing from the room. He sees me. He sees Margrethe. He doesn't see himself.

Heisenberg: Two thousand million people in the world, and the one who has to decide their fate is the only one who's always hidden from me. (87)

Just as Margrethe has explained in an earlier scene, on his own, Heisenberg cannot really know why he came to Copenhagen because he doesn't know the contents of his own mind; his own mind is the one bit of the universe he can't see. On the heels of this scene, Heisenberg and Bohr go outdoors for their walk, a chance to have their momentous conversation out of earshot of any bugs planted in Bohr's house by the Gestapo.

Bohr: With careful casualness he begins to ask the question he's prepared.

Heisenberg: Does one as a physicist have the moral right to work on the practical exploitation of atomic energy?

Margrethe: The great collision.

Bohr: I stop. He stops . . .

Margrethe: This is how they work.

Heisenberg: He gazes at me, horrified.

Margrethe: Now at last he knows where he is and what he's doing.

There we have it, a moment of knowing: Heisenberg can glimpse his own intentions, but only through the horror Bohr's face reflects as he gazes back at Heisenberg. As soon as this knowing interaction has taken place, Bohr uses the momentum of his anger to fly off into the night. But he stops short. He has an idea for how to get at this issue once and for all. He suggests a thought experiment.

Bohr: Let's suppose for a moment that I don't go flying off into the night. Let's see what happens if instead I remember the paternal role I'm supposed to play. If I stop, and control my anger, and turn to him. And ask him why.

Heisenberg: Why?

Bohr: Why are you confident that it's going to be so reassuringly difficult to build a bomb with [the isotope uranium] 235? Is it because you've done the calculation?

Heisenberg: The calculation?

Bohr: Of the diffusion in 235. No. It's because you haven't calculated it. You haven't considered calculating it. You hadn't consciously realized there was a calculation to be made.

Heisenberg: And of course now I have realized. In fact it wouldn't be that difficult. Let's see . . . Hold on . . .

Bohr: And suddenly a very different and very terrible new world begins to take shape . . .

And then (in the productions I've seen) the terrible sound of a shattering bomb blast fills the theater. As the blast subsides, once again a clarification of the issues comes from Margrethe.

Margrethe: That was the last and greatest demand that Heisenberg made on his friendship with you. To be understood when he couldn't understand himself. And that was the last and greatest act of friendship for Heisenberg that you performed in return. To leave him misunderstood.

Better for everyone that Heisenberg, like all of us, is shielded from shining a light on all the dark corners of the mind. For if Heisenberg's conscious mind had had access to all its subconscious thoughts, then Hitler might have been in possession of an atomic bomb, and after the dust settled, the world might have found itself in a vastly different geopolitical configuration. A good thing that we have this limitation—it's the uncertainty at the heart of things that saves our weary souls.

Bohr: Before we can lay our hands on anything, our life's over.

Heisenberg: Before we can glimpse who or what we are, we're gone and laid to dust.

Bohr: Settled among all the dust we raised.

Margrethe: And sooner or later there will come a time when all our children are laid to dust, and all our children's children.

Bohr: When no more decisions, great or small, are ever made again. When there's no more uncertainty, because there's no more knowledge.

Margrethe: And when all our eyes are closed, when even our ghosts are gone, what will be left of our beloved world? Our ruined and dishonoured and beloved world?

Heisenberg: But in the meanwhile, in this most precious meanwhile, there it is. The trees in Faelled Park. Gammertingen and Biberach and Mindelheim. Our children and our children's children. Preserved, just possibly, by that one short moment in Copenhagen. By some event that will never quite be located or defined. By that final core of uncertainty at the heart of things.

In the end it's because of our humanity—because of our limitations, because we can't ever truly know ourselves—that we survive.

This is how the play ends. But where, you might wonder, does this conclusion leave us with respect to the question of moral judgment and accountability? Frayn makes another important move in the final draft that can perhaps shed further light on this key question. In the final draft, Frayn drives home the point that he sets out to make (at least he speaks about the play as if he knows something of his own intentions): because we can't fully know Heisenberg's intentions, we can't fairly judge him. Ironically, however, Frayn plants his own judgments about Bohr throughout the play. It is Bohr, not Heisenberg, Frayn tells his audience, who wound up working on an atom bomb project that resulted in the deaths of tens of thousands of innocent people (a reference to Bohr's contributions to the U.S. bomb project at Los Alamos following his close escape from the Nazis in 1943).[10] It is Bohr (along with his student John Wheeler) who helped to develop a theory of nuclear fission. Bohr is the one who shot another physicist . . . with a cap pistol. (Only well into the scene do we learn the true nature of the weapon and the fact that it was all part of a playful interchange among colleagues. The cap pistol reappears near the end of the play as Heisenberg suggests that Bohr could have killed him in 1941 if he really thought Heisenberg was busy devising a bomb for Hitler, without even having to directly pull the trigger, by a simple indiscretion that would have tipped off the Gestapo about some detail of their meeting and resulted in Heisenberg being murdered by the Gestapo for treason.) More than once Frayn has us watch Bohr relive an unspeakably horrible moment in his life: Bohr stands aboard a sailing vessel and watches his oldest son drown. What role does this series of repetitions within repetitions play?

Heisenberg: Again and again the tiller slams over. Again and again . . .
Margrethe: Niels turns his head away . . .
Bohr: Christian reaches for the lifebuoy . . .
Heisenberg: But about some things even they never speak.
Bohr: About some things even we only think.
Margrethe: Because there's nothing to be said.

One shudders to think that an author would be willing to wield this deeply painful personal tragedy for the purpose of layering Bohr with every (un)-imaginable kind of life-and-death responsibility, but this unthinkable hypothesis fits all too neatly with the sleight of hand by which Frayn attempts to shift responsibility from Heisenberg to Bohr. Yes, we are told that Bohr was held back from jumping in and going after Christian, but as we watch Bohr's ghost being haunted by the memory over and over again, the terrible suggestion that some things shouldn't be said floats in the air. Can it be . . . isn't it the case that in the reiteration of the unspeakable, the unspeakable is spoken? And then there are the loving, yet all too facile, denials of Bohr's responsibility by Margrethe, which, of course, only serve to highlight his responsibility.

Heisenberg: He [Oppenheimer] said you made a great contribution.
Bohr: Spiritual, possibly. Not practical.
Heisenberg: Fermi says it was you who worked out how to trigger the Nagasaki bomb.
Bohr: I put forward an idea.
Margrethe: You're not implying that there's anything that *Niels* needs to explain or defend?
Heisenberg: No one has ever expected him to explain or defend anything. He's a profoundly good man.

All these subcritical pieces, these suggestions of Bohr's guilt planted throughout the play, come to an explosive climax just near the end when Frayn unleashes the idea of a "strange new quantum ethics," proposing its implications for the moral dilemma we are faced with:

Heisenberg: Meanwhile you were going on from Sweden to Los Alamos.
Bohr: To play my small but helpful part in the deaths of a hundred thousand people.
Margrethe: Niels, you did nothing wrong!
Bohr: Didn't I?
Heisenberg: Of course not. You were a good man, from first to last, and no one could ever say otherwise. Whereas I . . .
Bohr: Whereas you, my dear Heisenberg, never managed to contribute to the death of one single solitary person in all your life.

This powerful scene is one that remains imprinted in the minds of many audience members. And it's not surprising that it would: finally there is some resolution—a moral ground to stand on—something definite and concrete to hold onto amid the swirl of ghosts and uncertainties. And so is it any wonder that even though Frayn proceeds to disown this conclusion, audiences leave the play with the impression that if anyone should be held accountable for moral infractions, it is Bohr, not Heisenberg?

Surely Frayn is right to remind the audience that while the play focuses on German efforts to build the bomb, the United States had its own highly organized and well-funded wartime bomb project in the desert of Nevada, and the collective work at Los Alamos produced two different kinds of bombs—"fat man" (a plutonium-based device) and "thin man" (a bomb based on the fissioning of uranium-235)—and one of each kind was dropped on two cities in Japan, killing tens of thousands of innocent people. (What of the possibility that, whatever the nature of Heisenberg's intentions, his visit to Bohr in 1941 helped accelerate the U.S. bomb project, resulting in the use of atomic weapons against the Japanese before the war's official end?[11] Are things really so cut and dry that the dropping of atomic bombs on Japanese cities implicates Bohr while absolving Heisenberg?) But Frayn doesn't raise the issue to help us confront these relevant historical facts and the moral concerns they raise; rather, he uses it only to turn the tables so that we direct our moral outrage away from Heisenberg.

Frayn doesn't directly endorse this conclusion (at least not in the play).[12] In fact, he accuses audience members who leave with this impression of having made the embarrassing mistake of taking this "faux" conclusion seriously when he was obviously being ironic. Let's take a look at how Frayn (says he) accomplishes this ironic twist. Immediately following the foregoing exchange (where Bohr is held accountable for the deaths of one hundred thousand people, and Heisenberg is judged as innocent), Frayn has Heisenberg explain in an ironic passage that to judge people "strictly in terms of observable quantities" would constitute a strange new quantum ethics. Now, since the audience has been anticipating a new quantum-informed ethics all along and the passage itself involves a rather subtle point about quantum physics (what's this talk about restricting considerations to "observable quantities" all of a sudden?), it's perhaps not surprising that the irony has been lost on many a spectator, including some reviewers.

In other words, the move that Frayn makes to distance himself from the conclusion he throws out as bait to a hungry audience filled with anticipation (a conclusion that fingers Bohr instead of Heisenberg) is this: using irony, Frayn has Heisenberg question the application of a rather subtle aspect of his uncertainty principle (which is neither explained nor raised elsewhere in the play) to the situation of moral judgment. Here's the crucial exchange:

> *Bohr*: Heisenberg, I have to say—if people are to be measured strictly in terms of observable quantities . . .
>
> *Heisenberg*: Then we should need a strange new quantum ethics.

The physics point that Bohr begins to speak about is that Heisenberg, the historical figure, insisted (according to the positivist tenet) that one shouldn't presume anything about quantities that are not measurable, indeed that one should restrict all considerations to observable quantities. The way Frayn wields this point is this: if we follow the uncertainty principle, we would conclude that we shouldn't presume *anything* about intentions (since we can't know anything about them) and therefore all we have to base our moral judgments on is our actions. This is what Frayn calls a "strange new quantum ethics." And the cue we are given that this is *not* the conclusion we should walk away with is Heisenberg's lengthy homily on how if we made judgments only on the basis of actions, then the SS man who didn't shoot him when he had his chance near the war's end would go to heaven (presuming, of course, this was the only moral decision this particular devotee of Hitler faced during the long war). That's it. A bit too quick, perhaps? If Frayn had spelled out this key point more directly, he might have put it this way: we shouldn't rely on "observables"—that is, mere actions stripped of all intentions—to make moral judgments. (Surely you didn't expect that Frayn would have us rely strictly on historical facts about what happened to sort things out?) So where are we now? We can't judge people on either their intentions or their actions. Is there anything we can hold on to as the play ends and we gather up our belongings to leave the theater?

Frayn ends the play by presuming to help us take solace in the fact that uncertainty is not our undoing but our savior: it is the very unknowability of intentions, that is, our principled *inability* to truly judge one another, that saves our weary souls. This final conclusion—the "real conclusion"—harkens back to the earlier scene when Bohr turns around and helps Heisenberg to bring his unconscious intentions to light with the apocalyptic result that Heisenberg does the calculation and Hitler winds up with atomic weapons. Better that we don't know.

And so in the end, after a whirlwind of moral questions and uncertainties that surround, inhabit, and haunt the characters and the audience, we are left only with the slim and rather pat suggestion that the inherent uncertainty of the universe is our one salvation. All our moral searching is abruptly halted, frozen at a moment of time before Armageddon, and left as a mere shadow of itself cast on the wall that denies us access to our own souls. We are left wandering aimlessly through a barren landscape with no markers, no compass, only an empty feeling that quantum theory is somehow at once a manifestation of the mystery that keeps us alive and a cruel joke that deprives us of life's meaning. Given the recent reinvigoration of nuclear weapons programs around the globe, the suggestion that the absence of a moral or ethical ground will inevitably, or could even possibly, forestall the apocalypse portended by the play's end falls flat, to say the least. But need we follow the reasoning we've been offered into the despair of a moral wasteland laid bare by the explosion of absolute certainty? Is it true that quantum physics envelops us in a cloud of relativist reverie that mushrooms upward toward the heavens and outward encompassing all the earth, leaving us with no remedy, no recourse, no signpost, no exit?

I would argue, on the contrary, that quantum theory leads us out of the morass that takes absolutism and relativism to be the only two possibilities. But understanding how this is so requires a much more nuanced and careful reading of the physics and its philosophical implications than Frayn presents. I first review some of the main difficulties and then proceed to map out an alternative.

As we have seen, by Frayn's own admission, the parallel that he draws between physical and psychological uncertainties is limited and poorly specified. As with many such attempts to discern the implications of quantum mechanics on the basis of mere analogies, the alleged implications that are drawn, such as the assertion that our knowledge of ourselves and of others is necessarily limited, ultimately do not depend in any deep way on understanding the lessons of quantum physics. Surely there is no reason to invoke the complexities of this theory to raise such a conjecture about the limits to human knowledge. (Freud, for one, does not rely on quantum physics for his theory of the unconscious.) It would have been one thing if, for example, we had been offered a more nuanced or revised understanding of the nature of intentionality or causality. But ultimately it seems that such methods (intentionally or otherwise) are only out to garner the authority of science for some theory or proposition that someone wanted to advance anyway and could have advanced without understanding anything at all about quantum physics. (Of course, when the stakes are coming to Heisenberg's rescue, a clever use of the uncertainty principle is perhaps too much to resist.)

Another crucial point that I have yet to discuss is the fact that Frayn continually confuses the epistemological and ontological issues—issues concerning the nature of knowledge and the nature of being. And yet these are central elements in a heated debate between Bohr and Heisenberg concerning the correct interpretation of quantum physics, as I will explain. Before moving on to specify the nature of my own (nonanalogical) approach, I want to explore this issue further, since it entails a key point that is crucial for any project that seeks to understand the wider implications of quantum physics: the fact that there are multiple competing interpretations of quantum mechanics. One point that is particularly relevant for *Copenhagen* (and for my project) is the fact that there are significant differences between the interpretations of Bohr and Heisenberg. Frayn raises this point in the play but then proceeds to confuse the important differences between them.

Quite unexpectedly, Frayn brings to light the little-known and seldom-acknowledged but crucial historical fact that Heisenberg ultimately acquiesced to Bohr's point of view and made his concession clear in a postscript to the paper on his famous uncertainty principle. And yet, bizarrely, Frayn then proceeds to follow Heisenberg's (self-acknowledged) erroneous interpretation. It is not simply that this is yet one more source of tension between these two giants of the physics world; rather, the point is that there are significant, indeed far-reaching, differences between their interpretations and their respective philosophical implications. The question of what implications follow from *complementarity* (not uncertainty) is a specter that haunts this play. Frayn inexplicably buries the difference without putting it to rest.[13]

Let's take a brief look at some of the crucial issues.

In a key scene in the play, the audience learns about the intense disagreement between Bohr and Heisenberg concerning Heisenberg's uncertainty principle.[14] The nature of the difference between their views is not clearly laid out in the play, but it can be summarized as follows: For Bohr, what is at issue is *not* that we cannot *know* both the position and momentum of a particle simultaneously (as Heisenberg initially argued), but rather that particles do not *have* determinate values of position and momentum simultaneously. While Heisenberg's point—that in measuring any of the characteristics of a particle, we necessarily disturb its premeasurement values, so that the more we know about a particle's position, the less we will know about its momentum (and vice versa)—seems at least believable, Bohr's point is utterly counterintuitive and unfamiliar. In essence, Bohr is making a point about the nature of reality, not merely our knowledge of it. What he is doing is calling into question an entire tradition in the history of Western metaphysics: the belief that the world is populated with individual things with their own independent sets of determinate properties. The lesson that Bohr takes from quantum physics is very deep and profound: there aren't little things wandering aimlessly in the void that possess the complete set of properties that Newtonian physics assumes (e.g., position and momentum); rather, there is something fundamental about the nature of measurement interactions such that, given a particular measuring apparatus, certain properties *become determinate*, while others are specifically excluded. Which properties become determinate is not governed by the desires or will of the experimenter but rather by the specificity of the experimental apparatus.[15]

Thus there is still an important sense in which experiments can be said to be objective. Significantly, different quantities become determinate using different apparatuses, and it is not possible to have a situation in which all quantities will have definite values at once—some are always excluded. This makes for two "complementary" sets of variables: for any given apparatus, those that are determinate are said to be complementary to those that are indeterminate, and vice versa. Complementary variables require different—mutually exclusive—apparatuses (e.g., one with fixed parts and one with movable parts) for their definition, and therefore these variables are reciprocally determinable (when one is well defined, the other can't be). (I discuss these issues in detail in chapter 3.) Significantly, as Frayn points out, Heisenberg acquiesced to Bohr's interpretation: it is complementarity that is at issue, not uncertainty.

With this important difference in mind, it's hard to resist the temptation to contemplate a new play, a rewriting of Frayn's *Copenhagen* using Bohr's complementarity principle rather than Heisenberg's uncertainty principle as a basis for analysis. I want to be clear that I am *not* suggesting that the difficulties with Frayn's play can be rectified by simply substituting one principle for the other and performing the same kind of analogical thought experiment to consider the moral and epistemological issues at hand. But I do want to briefly indulge in this exercise in a limited fashion, recognizing that there is no expectation of providing a rigorous analysis of the important issues at hand simply by making this shift. The point of the exercise is to get a sense of what a more careful consideration of quantum physics and its implications might bring to the surface. In this way we can at least get some feel for *what* philosophical issues are raised and *what* concepts might need to be rethought if we take quantum physics seriously, even though this method may not help us to understand *how* the issues can be resolved and the relevant concepts reconceptualized.

Let's return to the question of Heisenberg's intentions in visiting Bohr in the autumn of 1941. Interestingly enough, there is already an important hint in *Copenhagen* that suggests how we might proceed if we want to take Bohr's complementarity principle as the basis for our analysis. We can zoom in on just the right passage by thinking of Margrethe not "merely" as Bohr's wife but as an integral part of Bohr (as Bohr says in reference to his partner, "I was formed by nature to be a mathematically curious entity: not one but half of two").[16]

Margrethe: Complementarity again. Yes?

Bohr: Yes, yes.

Margrethe: I've typed it out often enough. If you're doing something you have to concentrate on you can't also be thinking about doing it, and if you're thinking about doing it then you can't actually be doing it. Yes?

Ironically, Frayn draws the conclusion from this statement of complementarity (by Margrethe) that doing something and thinking about what you're doing means that Heisenberg doesn't know why he came to Copenhagen in 1941. But, in fact, it (or actually the relevant elaboration of the point) has quite different and much more far-reaching and profound implications. Frayn takes quite a leap here, and we would do well to go more slowly. Suppose that the activity that you're engaged in doing happens to be thinking. Then it follows (from Margrethe's statement of complementarity) that what you are prohibited from doing is both thinking about something and thinking about thinking about it. That is, you can't both think about something and also reflect on your own thinking about the matter. This is because you need to make a choice between two complementary situations: either you think about something, in which case that something is the object of your thoughts, or you examine your process of thinking about something, in which case your thoughts about what you are thinking (about something), and not the something itself, are the object of your thoughts.[17]

Now let's assume that one of the things you're interested in discerning (by attempting to observe your thoughts) is your intentions concerning the thing you're thinking about. We can then deduce that there is a reciprocal or complementary relationship between thinking about something and knowing your intentions (concerning the matter). Now, the implication of this reciprocal relationship we've uncovered is *not*, as Frayn suggests, that we can't *know* them simultaneously but rather that we can't *have* definite thoughts about something and definite intentions concerning that thing simultaneously. That is, the point is that *there is no determinate fact of the matter* about both our thoughts and our intentions concerning the object of our thoughts. What we learn from this is that the very notion of intentionality needs to be reevaluated. We are used to thinking that there are determinate intentional states of mind that exist "somewhere" in people's brains and that if we are clever enough we can perform some kind of measurement (by using some kind of brain scan, for example) that would disclose the intentions (about some determinate something) that exist in a person's mind. But according to Bohr, we shouldn't rely on the metaphysical presuppositions of classical physics (which Bohr claims is the basis for our common-sense perception of reality); rather, what we need to do is attend to the actual experimental conditions that would enable us to measure and make sense of the notion of intentional states of mind. In the absence of such conditions, not only is the notion of an "intentional state of mind" meaningless, but there is no corresponding determinate fact of the matter. To summarize, the crucial point is not merely that intentional states are inherently unknowable, but that *the very nature of intentionality needs to be rethought.*

Frayn's whole play is structured around the attempt to determine Heisenberg's intentions, as if there were determinate facts of the matter about them at all times. By contrast, Bohr's point is that the very notion of an intentional state of mind, like all other classical properties, cannot be taken for granted. To speak in a meaningful way about an intentional state of mind, we first need to say what material conditions exist that give it meaning and some definite sense of existence. But what would it mean to specify such conditions? What, for example, would constitute the appropriate set of material conditions for the complex political, psychological, social, scientific, technological, and economic situation that Heisenberg finds himself in, where matters of race, religion, nationality, ethnicity, sexuality, political beliefs, and mental and physical health are material to Nazi thinking? And this is surely an abbreviated list. And what does "material" mean?

Furthermore, with such a complex set of apparatuses at work, we are led to question whether it makes sense to talk about an intentional state of mind as if it were a property of an individual. Let's return to the play for a brief moment. While Heisenberg struggles to get his point across that he tried desperately to stay in control of the nuclear physics program in Germany and slow down the progress of the development of an atom bomb, Bohr points out that there was an important sense in which he was not in control of the program, but rather the program was controlling him: "Nothing was under anyone's control by that time!" But if the program is controlling Heisenberg rather than the reverse, what accounts for his intentional states? Whom do they belong to? Is individualism a prerequisite for figuring accountability? Are the notions of intentionality and accountability eviscerated? Despite these fundamental challenges to some of our core concepts, according to (the historical) Bohr, objectivity and accountability need not be renounced. (See especially chapters 3 and 4 for an in-depth discussion of Bohr's views on objectivity and accountability.)

In summary, the shift from Heisenberg's interpretation to Bohr's undermines the very premise of the play. Frayn structures the play around the assumption that moral judgments are tied up with questions of an individual's intentions. But in Bohr's account intentionality cannot be taken for granted: intentions are not preexisting determinate mental states of individual human beings. A sophisticated argument needs to be given here, but this exercise provides an important hint of what a more rigorous analysis may reveal: that attending to the complex material conditions needed to specify "intentions" in a meaningful way prevents us from assuming that "intentions" are (1) preexisting states of mind, and (2) properly assigned to individuals. Perhaps intentionality might better be understood as attributable to a complex network of human and nonhuman agents, including historically specific sets of material conditions that exceed the traditional notion of the individual. Or perhaps it is less that there is an assemblage of agents than there is an entangled state of agencies. These issues, however, cannot be resolved by reasoning analogically; they require a different kind of analysis.

This thought experiment also suggests that moral judgment is not to be based *either* on actions *or* on intentions alone; rather, the very binary between "interior" and "exterior" states needs to be rethought, and both "internal" and "external" factors—intentionality and history—matter. But this exercise alone does not reveal *how* they matter and *how* they stand in relationship to one another. We learn *what* issues may arise in considering the implications of Bohr's interpretation, but we need a much more careful, detailed, and rigorous analysis to really get a handle on them. For example, questions of causality are surely significant in coming to terms with these important issues, but further exploration of Bohr's ideas reveals that the very notion of causality must be reconsidered, since the traditional conception—which presents only the binary options of free will and determinism—is flawed. But if causality is reworked, then power needs to be rethought. (Power relations cannot be understood as either determining or absent of constraints within a corral that merely limits the free choices of individuals.) Agency needs to be rethought. Ethics needs to be rethought. Science needs to be rethought. Indeed, taking Bohr's interpretation seriously calls for a reworking of the very terms of the question about the relationship between science and ethics. Even beyond that, it undermines the metaphysics of individualism and calls for a rethinking of the very nature of knowledge and being. It may not be too much of an exaggeration to say that every aspect of how we understand the world, including ourselves, is changed.

In summary, this thought experiment only provides us with the briefest glimpse of the momentous changes in our worldview that Bohr's interpretation of quantum physics entails. It gives us some indication of *what* needs to be rethought, but not a basis for understanding *how* to rethink the relevant issues. Also, reasoning by analogy can easily lead one astray. And furthermore, it posits separate categories of items, analyzes one set in terms of the other, and thereby necessarily excludes by its own procedures an exploration of the nature of the relationship between them. Indeed, even Bohr erred in trying to understand "the lessons of quantum physics" by drawing analogies between physics and biology or physics and anthropology. Ultimately Bohr was interested not in specifying one-to-one correspondences between these components but in focusing our attention on the conditions for the use of particular concepts so that we do not fall into complacency and take them for granted; but he often lost his way, and he was only able to hint at the implications he sensed were implicit in his work. What is needed to develop a rigorous and robust understanding of the implications of Bohr's interpretation of quantum physics is a much more careful, detailed, and thorough analysis of his overall philosophy.

In this book I offer a rigorous examination and elaboration of the implications of Bohr's philosophy-physics (physics and philosophy were one practice for him, not two). I avoid using an analogical methodology; instead, I carefully identify, examine, explicate, and explore the philosophical issues.[18] I am not interested in drawing analogies between particles and people, the micro and the macro, the scientific and the social, nature and culture; rather, I am interested in understanding the epistemological and ontological issues that quantum physics forces us to confront, such as the conditions for the possibility of objectivity, the nature of measurement, the nature of nature and meaning making, and the relationship between discursive practices and the material world.

I also do not assume that a meaningful answer to the questions about the relationship between science and ethics can be derived from what physics alone tells about the world. Physics can't be bootstrapped into giving a full account of the social world. It would be wrong to simply assume that people are the analogues of atoms and that societies are mere epiphenomena that can be explained in terms of collective behavior of massive ensembles of individual entities (like little atoms each), or that sociology is reducible to biology, which is reducible to chemistry, which in turn is reducible to physics. Quantum physics undercuts reductionism as a worldview or universal explanatory framework. Reductionism has a very limited run.

What is needed is a reassessment of physical and metaphysical notions that explicitly or implicitly rely on old ideas about the physical world—that is, we need a reassessment of these notions in terms of the best physical theories we currently have. And likewise we need to bring our best social and political theories to bear in reassessing how we understand social phenomena, including the material practices through which we divide the world

into the categories of the "social" and the "natural."[19] What is needed is an analysis that enables us to theorize the social and the natural together, to read our best understandings of social and natural phenomena through one another in a way that clarifies the relationship between them. To write matter and meaning into separate categories, to analyze them relative to separate disciplinary technologies, and to divide complex phenomena into one balkanized enclave or the other is to elide certain crucial aspects by design. On the other hand, considering them together does not mean forcing them together, collapsing important differences between them, or treating them in the same way, but means allowing any integral aspects to emerge (by not writing them out before we get started).

OVERVIEW OF THE BOOK

This book demonstrates how and why we must understand in an *integral* way the roles of human and nonhuman, material and discursive, and natural and cultural factors in scientific and other practices. I draw on the insights of some of our best scientific and social theories, including quantum physics, science studies, the philosophy of physics, feminist theory, critical race theory, postcolonial theory, (post-)Marxist theory, and poststructuralist theory. Based on a "diffractive" methodological approach, I read insights from these different areas of study through one another. My aim in developing such a diffractive methodology (chapter 2) is to provide a transdisciplinary approach that remains rigorously attentive to important details of specialized arguments within a given field, in an effort to foster constructive engagements across (and a reworking of) disciplinary boundaries. In particular, this approach provides important theoretical tools needed to move conversations in science studies, feminist studies, and other (inter)disciplinary studies beyond the mere acknowledgment that both material and discursive, and natural and cultural, factors play a role in knowledge production by examining *how* these factors work together, and how conceptions of materiality, social practice, nature, and discourse must change to accommodate their mutual involvement. I also show that this method is sufficiently robust to build meaningful conversations between the sciences and other areas of study and to contribute to scientific research.

This book contributes to the founding of a new ontology, epistemology, and ethics, including a new understanding of the nature of scientific practices. In fact, I show that an empirically accurate understanding of scientific practice, one that is consonant with the latest scientific research, strongly suggests a fundamental inseparability of epistemological, ontological, and ethical considerations. In particular, I propose "agential realism" as an epistemological-ontological-ethical framework that provides an understanding of the role of human *and* nonhuman, material *and* discursive, and natural *and* cultural factors in scientific and other social-material practices, thereby moving such considerations beyond the well-worn debates that pit constructivism against realism, agency against structure, and idealism against materialism. Indeed, the new philosophical framework that I propose entails a rethinking of fundamental concepts that support such binary thinking, including the notions of matter, discourse, causality, agency, power, identity, embodiment, objectivity, space, and time.

The starting point for this transdisciplinary engagement is the philosophically rich epistemological framework proposed by the physicist Niels Bohr. I extend and partially revise his philosophical views in critical conversation with current scholarship in science studies, the philosophy of science, physics, and various interdisciplinary approaches that might collectively be called "critical social theories" (e.g., feminist theory, critical race theory, queer theory, postcolonial theory, (post-)Marxist theory, and poststructuralist theory). Bohr's philosophy-physics is a particularly apt starting point for thinking the natural and social worlds together and gaining some important clues about how to theorize the nature of the relationship between them, since his investigations of quantum physics open up questions not only about the nature of nature but also about the nature of scientific and other social practices. In particular, Bohr's naturalist commitment to understanding both the nature of nature and the nature of science according to what our best scientific theories tell us led him to what he took to be the heart of the lesson of quantum physics: *we are a part of that nature that we seek to understand.* Bohr argues that scientific practices must therefore be understood as interactions among component parts of nature and that our ability to understand the world hinges on our taking account of the fact that our knowledge-making practices are social-material enactments that contribute to, and are a part of, the phenomena we describe.

Ultimately, however, the far-reaching implications of Bohr's epistemology and his posthumanist insights are cut short by his unexamined humanist commitments—his anti-Copernicanism, as it were, which places the human back at the center of the universe. In particular, Bohr cements human concepts and knowers into the foundations of the ontological relations of knowing. This creates difficulties for developing a coherent interpretation of quantum physics, as well as for examining its larger implications. As I

explain in chapter 7, while the majority of physicists claim allegiance to the so-called Copenhagen interpretation of quantum physics, which is largely based on contributions from Bohr and other members of the Copenhagen circle, physicists and philosophers of physics who are interested in issues in the foundations of quantum physics have expressed discomfort with Bohr's remnant humanism. The "distasteful" presence of human concepts and human knowledge in the foundations of the theory has been a major stumbling block.

I imagine that poststructuralist theorists and scholars in science studies will also find much to embrace in Bohr's philosophy-physics, but there is good reason to believe that they too will balk at his humanism for their own (very different) reasons. For example, both groups of scholars will most likely find sympathy with Bohr's position that neither the subjects nor the objects of knowledge practices can be taken for granted, and that one must inquire into the material specificities of the apparatuses that help constitute objects and subjects. Indeed, poststructuralists would be quick to point out that a commitment to understanding the differential constitution of the human subject does not sit easily with humanism's essentialist conception of the human. On the contrary, humanism takes for granted much of what needs to be investigated. Scholars in science studies have a very different set of concerns. Their disavowal of humanism is based on an interest in the ways in which the "human" and its others (e.g., including machines and nonhuman animals) are conceptualized, produced, and reworked through scientific and technological practices. Needless to say, they don't have to dig very far to find justification for their rejection of humanism, since the news serves up daily reminders that science and technology are actively remaking the nature of the "human." Indeed, the recent convergence of biotechnologies, information technologies, and nanotechnologies reconfigures the human and its others so rapidly that it is already overloading the circuits of the human imagination.

At the same time, I will argue that Bohr's insights can be helpful in revealing and explicating difficulties in these other areas of study, and in posing possible remedies and directions for revision or further elaboration. In particular, some important poststructuralist, science studies, and physics insights are also cut short by their own remnant anthropocentrist and representationalist assumptions. Reading these insights through one another can be helpful in dislodging these unwanted remnants, thereby providing more refined tools that can be useful for addressing a host of different (inter)disciplinary concerns.

Chapter 1 presents the main problematic of the book: the challenge and necessity of adequately theorizing the relationship between discursive practices and the material world. I begin with a discussion of representationalism—the idea that representations and the objects (subjects, events, or states of affairs) they purport to represent are independent of one another. I discuss some of the problems, difficulties, and limitations of representationalism. I then consider a class of alternative approaches to representationalism that can collectively be designated as "performative." Performative approaches call into question the basic premises of representationalism and focus inquiry on the practices or performances of representing, as well as on the productive effects of those practices and the conditions for their efficacy.

In recent years, both science studies scholars and critical social theorists have pursued performative alternatives to social constructivist approaches (which, much like their scientific realist counterparts, are based on representationalist beliefs). The move toward performative alternatives to representationalism changes the focus from questions of correspondence between descriptions and reality (e.g., do they mirror nature or culture?) to matters of practices or doings or actions. By and large, performative accounts offered by science studies scholars, on the one hand, and social and political theorists, on the other, have led parallel lives with surprisingly little exchange between them. I point out some of the strengths and weaknesses of these different performative approaches and (in chapter 4) put them in conversation with one another in an effort to sharpen both sets of tools, or rather to develop a performative account that takes both sets of insights seriously.

Chapter 2 serves two seemingly disparate purposes: it introduces the important physical phenomenon of diffraction, and it discusses questions of methodology. I will explain what these issues have to do with each other shortly, but first I want to offer a brief description of the physical phenomenon of diffraction. Diffraction is a phenomenon that is unique to wave behavior. Water waves exhibit diffraction patterns, as do sound waves, and light waves. Diffraction has to do with the way waves combine when they overlap and the apparent bending and spreading out of waves when they encounter an obstruction. Diffraction phenomena are familiar from everyday experience. A familiar example is the diffraction or interference pattern that water waves make when they rush through an opening in a breakwater or when stones are dropped in a pond and the ripples overlap. (While some physicists continue to abide by the purely historical distinction between diffraction and interference phenomena, I use the terms "diffraction" and

"interference" interchangeably. That is, I side with the physicist Richard Feynman and others who drop this distinction on the basis that what is at issue in both cases is the physics of the superposition of waves.)[20]

As I explain in chapter 2, diffraction is an apt overarching trope for this book. Diffraction plays a crucial role in sorting out some key issues in quantum physics. Perhaps one of the most well known dilemmas in quantum physics is the "wave-particle duality paradox": experimental evidence at the beginning of the twentieth century exhibited seemingly contradictory features—on the one hand, light seemed to behave like a wave, but under different experimental circumstances, light seemed to behave like a particle. Given these results, what can we conclude about the nature of light—is it a particle or a wave? Remarkably, it turns out that similar results are found for matter: under one set of circumstances, electrons behave like particles, and under another they behave like waves. Hence what lies at the heart of the paradox is the very nature of nature. As the book progresses, I develop deeper and deeper insights about this profound set of issues, and diffraction phenomena play a key role all along in helping to illuminate the nature of nature.

Furthermore, as I explain in chapter 2, diffraction turns out to be an apt (material and semiotic) figuration for the methodological approach that I use and develop. There is a long history of using vision and optical metaphors to talk and theorize about knowledge. The physical phenomenon of reflection is a common metaphor for thinking—a little reflection shows this to be the case. Donna Haraway proposes diffraction as an alternative to the well-worn metaphor of reflection. As Haraway suggests, diffraction can serve as a useful counterpoint to reflection: both are optical phenomena, but whereas reflection is about mirroring and sameness, diffraction attends to patterns of difference. One of her concerns is the way reflexivity has played itself out as a methodology, especially as it has been taken up and discussed by mainstream scholars in science studies. Haraway notes that "[reflexivity or reflection] invites the illusion of essential, fixed position, while [diffraction] trains us to more subtle vision" (1992). Diffraction entails "the processing of small but consequential differences," and "the processing of differences . . . is about ways of life" (ibid.). In this book, I further develop and elaborate these ideas, drawing on quantum understandings of diffraction phenomena and the results of some recent experiments. Ultimately, I argue that a diffractive methodology is respectful of the entanglement of ideas and other materials in ways that reflexive methodologies are not. In particular, what is needed is a method attuned to the entanglement of the apparatuses of production, one that enables genealogical analyses of how boundaries are produced rather than presuming sets of well-worn binaries in advance. I begin this elaboration in chapter 2, but the full display of its intricate patterns and reverberations with all the vibrancy, richness, and vitality of this remarkable physical phenomenon is manifest only in diffracting these insights through the grating of the entire set of book chapters.

One important aspect that I discuss is that diffraction does not fix what is the object and what is the subject in advance, and so, unlike methods of reading one text or set of ideas against another where one set serves as a fixed frame of reference, diffraction involves reading insights through one another in ways that help illuminate differences as they emerge: how different differences get made, what gets excluded, and how those exclusions matter.

For example, as I suggested earlier, if the goal is to think the social and the natural together, to take account of *how* both factors matter (not simply to recognize that they both do matter), then we need a method for theorizing the relationship between "the natural" and "the social" together without defining one against the other or holding either nature or culture as the fixed referent for understanding the other. What is needed is a diffraction apparatus to study these entanglements. One way to begin to build the needed apparatus is to use the following approach: to rethink the nature of nature based on our best scientific theories, while rethinking the nature of scientific practices in terms of our best understanding of the nature of nature and our best social theories, while rethinking our best social theories in terms of our best understanding of the nature of nature and the nature of scientific theories. A diffractive methodology provides a way of attending to entanglements in reading important insights and approaches through one another.

In chapter 3 I offer a unique interpretation of Bohr's philosophy-physics. Interpretations of Bohr's epistemological framework have been widely divergent. Bohr has been fashioned a positivist, an idealist, an instrumentalist, a (macro)phenomenalist, an operationalist, a pragmatist, a (neo-)Kantian, and a scientific realist by various mainstream historians and philosophers of science. In contrast, I argue that Bohr's philosophy does not fit neatly into any of these categories because it questions many of the dualisms on which these philosophical schools of thought are founded. For example, while Bohr's understanding of quantum physics leads him to reject the possibility that scientists can gain access to the "things-in-themselves," that is, the objects of investigation as they exist outside human conceptual frameworks, he does not subscribe to a Kantian noumena-phenomena distinction. And while Bohr's practice of physics shows that he holds a realist attitude toward his subject matter, he is not a realist in any conventional sense, since he believes that the interaction between the objects of investigation and what he calls "the agencies of observation" is not determinable and therefore cannot be "subtracted out" to leave a representation of the world as it exists independently of human beings.

Significantly, Bohr's epistemological framework, based on empirical findings in the atomic domain in the early twentieth century, offers a new understanding of fundamental philosophical issues such as the relationship between knower and known, the role of measurement, questions of meaning making and concept use, the conditions for the possibility of objective description, correct identification of the objective referent for measured properties, the nature of causality, and the nature of reality. Bohr's philosophy-physics contains important and far-reaching ontological implications, but unfortunately he stays singularly focused on the epistemological issues and does not make this contribution explicit or explicate his views on the nature of reality. He is explicit in stating that in his opinion quantum physics shows that the world surely does not abide by the ontology of Newtonian physics. One of the goals of this chapter is to extract the implicit ontological implications and explicate a consistent Bohrian ontology. Ontology, as much as epistemology, plays a crucial role in my agential realist elaboration of Bohr's philosophy-physics (see chapter 4).

In chapter 3 I suggest that there is an important sense in which Bohr's framework can be understood as offering a proto-performative account of scientific practices, including an account of the production of bodies and meanings. I develop this suggestion further in chapter 4 and further elaborate the performative dimensions of Bohr's account. In what sense is Bohr's account "proto-performative"? First of all, Bohr's careful analysis of measurement leads him to reject representationalism. Remarkably, Bohr calls into question representationalism's taken-for-granted stance toward *both* words and things. That is, unlike (some of) the poststructuralist and science studies accounts, which fully explicate and emphasize *either* the discursive *or* material nature of practices, Bohr takes hold of both dimensions at once. It is not unreasonable (although surely not expected) for a physicist to question accepted ideas concerning the nature of things, but Bohr also concerns himself with the nature of words, including questions of the nature of meaning, practices for making meaning, the conditions for the possibility of intelligibility, and the co-constitution of an excluded domain, a domain of unintelligibility—and this is a highly unusual line of questioning for a physicist. But even more remarkably, Bohr understands these issues—concerning word and world—to be inextricably linked. According to Bohr, our ability to understand the physical world hinges on our recognizing that our knowledge-making practices, including the use and testing of scientific concepts, are material enactments that contribute to, and are a part of, the phenomena we describe.

The details of Bohr's nuanced interrogation of the representationalist tenets embedded in Newtonian physics and concordant epistemologies are crucial. Therefore I do not skimp on the details of the physics issues involved, but I also do not assume that the reader has any background in physics. I have made every effort to make these ideas accessible even to readers who have no knowledge of physics. Bohr set the same standards for himself. He firmly believed that it was important to explain things using (extensions of) everyday concepts. This was as much a methodological and epistemological commitment on Bohr's part as it was about accessibility: too many important questions lay hidden in the mathematics, and it is crucial not simply to be able to calculate, but to understand what the physics is saying, what it means. It is also vital that I attend to the details of Bohr's philosophy-physics because in chapter 7 I turn my attention back to the physics and consider some of the foundational issues that continue to plague quantum physics. Only by attending to the rigorous details can we hear nature speak with any kind of clarity (as Einstein said, "God is in the details").

Chapter 4 is the core chapter of the book. Here I develop my central theoretical framework—agential realism. Agential realism is an epistemological, ontological, and ethical framework that makes explicit the integral nature of these concerns. This framework provides a posthumanist performative account of technoscientific and other naturalcultural practices.[21] By "posthumanist" I mean to signal the crucial recognition that nonhumans play an important role in naturalcultural practices, including everyday social practices, scientific practices, and practices that do not include humans.[22] But also, beyond this, my use of "posthumanism" marks a refusal to take the distinction between "human" and "nonhuman" for granted, and to found analyses on this presumably fixed and inherent set of categories. Any such hardwiring precludes a genealogical investigation into the practices through which "humans" and "nonhumans" are delineated and differentially constituted. A posthumanist performative account worth its salt must also avoid cementing the nature-culture dichotomy into its foundations, thereby enabling a genealogical analysis of how these crucial distinctions are materially and discursively produced.

A core section of the chapter explicates my proposed agential realist ontology. As I mentioned previously, Bohr keeps his focus on the epistemological issues throughout and unfortunately never spells out his ontological commitments or the ontological dimensions of his account. On the basis of the Bohrian ontology that I propose in chapter 3, as well as new experimental evidence discussed in chapter 7, and other considerations, I propose an agential realist elaboration in chapter 4.

As I argue in chapter 3, the primary ontological unit is not independent objects with independently determinate boundaries and properties but rather what Bohr terms "phenomena." In my agential realist elaboration, phenomena do not merely mark the epistemological inseparability of observer and observed, or the results of measurements; rather, *phenomena* are the *ontological* inseparability of agentially intra-acting components. (The notion of intra-actions figures centrally here—see hereafter.) Significantly, phenomena are not mere laboratory creations but basic units of reality. The shift from a metaphysics of things to phenomena makes an enormous difference in understanding the nature of science and ontological, epistemological, and ethical issues more generally.

The notion of intra-action is a key element of my agential realist framework. The neologism "intra-action" *signifies the mutual constitution of entangled agencies*. That is, in contrast to the usual "interaction," which assumes that there are separate individual agencies that precede their interaction, the notion of intra-action recognizes that distinct agencies do not precede, but rather emerge through, their intra-action. It is important to note that the "distinct" agencies are only distinct in a relational, not an absolute, sense, that is, *agencies are only distinct in relation to their mutual entanglement; they don't exist as individual elements.*[23]

Crucially, as I explain in chapter 4, *the notion of intra-action constitutes a radical reworking of the traditional notion of causality*. I can't emphasize this point enough. A lively new ontology emerges: the world's radical aliveness comes to light in an entirely nontraditional way that reworks the nature of both relationality and aliveness (vitality, dynamism, agency). This shift in ontology also entails a reconceptualization of other core philosophical concepts such as space, time, matter, dynamics, agency, structure, subjectivity, objectivity, knowing, intentionality, discursivity, performativity, entanglement, and ethical engagement.

Performative accounts that social and political theorists have offered focus on the productive nature of social practices and human bodies. By contrast, agential realism takes account of the fact that the forces at work in the materialization of bodies are not only social, and the bodies produced are not all human. Crucially, I argue that agential realism clarifies the nature of the causal relationship between discursive practices and material phenomena. That is, I propose a new understanding of how discursive practices are related to the material world. This is a significant result with far-reaching consequences for grasping and attending to the political possibilities for change, the responsible practice of science, and the responsible education of scientists, among other important shifts.

These proposed refigurations are explored by considering concrete examples. The third part of the book, "Entanglements and Re(con)figurations," continues the elaboration of key agential realist ideas introduced in chapter 4 and works through several different case studies. Here I demonstrate the usefulness of an agential realist approach for negotiating difficulties in some of the fields that I draw on, such as feminist theory, poststructuralist theory, physics, and science and technology studies. I also show that agential realism makes visible a range of different connections between these disparate fields that have not previously been explored.

In chapter 5, I consider one of the ways in which agential realism can be useful for thinking about specific issues that have been central to feminist theory, activism, and politics. The development of new reproductive technologies, including new visualizing technologies, continues to play a crucial role in the public discourse as well as in feminist theories of the body. Using the example of new reproductive technologies, I explore the significance of my posthumanist performative understanding of the materialization of bodies by explicitly considering its ability to take account of crucial material dimensions, such as material agency, material constraints, and material exclusions, that other accounts, including other performative accounts, neglect. In particular, I further examine the implications of my sympathetic but critical reading of Butler's theory of performativity begun in Chapter 4. Judith Butler's provocative theory of performativity, which links gender performativity to the materialization of sexed bodies, has received widespread attention in academic circles, especially among feminist and queer theory scholars. I argue that Butler's conception of materiality is limited by its exclusive focus on human bodies and social factors, which works against her efforts to understand the relationship between materiality and discursivity in their indissociability. I show how agential realism's reconceptualization of the nature of matter and discursive practices provides a means for taking account of the productive nature of natural as well as cultural forces in the differential materialization of nonhuman as well as human bodies. It thereby avoids the privileging of discursive over material concerns and the

reinscription of the nature-culture dualism that Butler's account inadvertently enacts. Crucially, it also corrects Butler's underestimation of the possibilities for agentially reconfiguring who or what comes to matter, and makes evident a much larger space of possibilities for change. (Chapter 5 is a revised version of a previously published work. The original structure has been maintained so that it is available in the form of an autonomous text, suitable for classroom use or other forums for discussion.)

In chapter 6, I consider how agential realism can contribute to a new materialist understanding of power and its effects on the production of bodies, identities, and subjectivities. This chapter specifically engages Leela Fernandes's ethnographic study of relations of production at a Calcutta jute mill, where questions of political economy and cultural identity are both at work on the shop floor. Central to my analysis is the agential realist understanding of matter as a dynamic and shifting entanglement of relations, rather than as a property of things. Drawing on specific developments in political theory, cultural geography, political economy, critical race theory, postcolonial theory, and feminist theory, I consider the dynamic and contingent materialization of space, time, and bodies; the incorporation of material-discursive factors (including gender, race, sexuality, religion, and nationality, as well as class, but also technoscientific and natural factors) in processes of materialization; the iterative (re)materialization of the relations of production; and the agential possibilities and responsibilities for reconfiguring the material-social relations of the world.

After developing the ontological and epistemological framework of agential realism, I return in chapter 7 to the field of physics. I begin this chapter with a review of some of the unresolved interpretational difficulties that have plagued quantum mechanics since its founding three-quarters of a century ago. During the past decade, technological progress in experimental physics has opened up an entirely new empirical domain: the world of "experimental metaphysics." That is, questions previously thought to be a matter solely for philosophical debate have been brought into the orbit of empirical inquiry. This is a striking development because it allows scientists to explore metaphysical issues in the laboratory (so much for the category "metaphysical"). I include in this chapter a review of key experimental findings that have important implications for understanding quantum physics. I also consider the possibility of using agential realism as the basis for a new interpretation, examine its potential for resolving certain long-standing paradoxes in the field, and compare it to some of the newer interpretations that have recently been proposed.

Significantly, then, my project departs from mainstream and feminist science studies in that it does not merely offer insights about the nature of scientific practices but also makes a constructive contribution to the field of science being studied. That is, my project is not merely a reflection on science but takes these insights about scientific practices and about nature (the two key ingredients in Bohr's interpretation) and diffracts them back onto the science itself, thereby making a specific scientific contribution to an active scientific research field (i.e., the foundations of quantum physics). In particular, I argue that the conceptual shifts derived from my diffractive methodology not only reconfigure our understanding of the nature of scientific and other material-discursive practices but also are significant and robust enough to actually form the basis for a new interpretation of quantum physics.

Importantly, the metaphysical questions that the new experiments address have wide-ranging implications beyond the domain of physics. The implications will surely be of interest to philosophers, especially those with naturalist inclinations. And despite a growing distaste for metaphysics, poststructuralist and other critical theorists will no doubt find much food for thought in the discussion of experiments that directly address questions of the nature of identity, time, and matter. As before, I try to make this chapter accessible to readers who have no background in physics. Physicists will also find much to ponder in this chapter, which includes a systematic review and philosophical exposition of key interpretative issues.

The concluding chapter, chapter 8, brings together the major themes in the book and explicates some of the key issues. Concrete examples of nanotechnologies, information technologies, and biotechnologies provide an opportunity for fleshing out these ideas and for analyzing some of the important genealogical elements of the apparatus contemporary physics uses to study entanglements. These technologies are inextricably intertwined, as are the issues they bring into focus: the intra-activity of becoming, the ontology of knowing, and the ethics of mattering. The entanglement of ontology, epistemology, and ethics is emphasized in this chapter. As the book unfolds, the complexity and richness of the phenomenon of diffraction become increasingly evident. In this chapter, I bring into focus the overall pattern that has been created (i.e., a diffraction pattern of diffraction as a changing phenomenon) and explain how the pattern itself is a matter of entanglement. Indeed, I argue that diffraction is not merely about differences, and certainly not differences in any absolute sense, but about the entangled nature of differences that matter. Significantly, difference is tied up with responsibility, as I explain in a final section of the chapter.

In this last chapter, I develop the basic elements of an agential realist understanding of ethics. I explain that ethical concerns are not simply supplemental to the practice of science but an integral part of it. But more than this, I show how *values are integral to the nature of knowing and being*. Objectivity is simultaneously an epistemological, ontological, and axiological issue, and questions of responsibility and accountability lie at the core of scientific practice. The correct identification of the objective referent of scientific practices of theorizing and experimenting requires an accounting of the ethical (as well as epistemological and ontological) concerns. It is not possible to extricate oneself from ethical concerns and correctly discern what science tells us about the world. Realism, then, is not about representations of an independent reality but about the real consequences, interventions, creative possibilities, and responsibilities of intra-acting within and as part of the world.[24] (It is perhaps worth noting at this juncture that we have come a long way from Frayn's proposal. It seems unlikely that even very careful analogical reasoning would have led us to this conclusion about the nature of the relationship between science and ethics.)

Since this book is lengthier than is fashionable these days, I offer some suggestions for different possible paths through the book for different readers. A word of caution before I do: as I have indicated, this book works as a diffraction grating, illuminating important material differences, relationalities, and entanglements in the lively dance of mattering, and it may be difficult to appreciate the intricacies of the pattern that is produced if significant segments of the book are skipped over. That said, it is undoubtedly the case that interesting patterns arise nonetheless in sampling different chapters, and different readers may find different samplings particularly worthwhile. Physicists and philosophers of science may be particularly interested in chapters 3, 4, and 7. These chapters taken together constitute a detailed examination of Bohr's philosophy-physics and offer a coherent reconstruction of the interpretative issues together with an accessible and systematic presentation of some important experimental results from the past decade. Chapter 5 was originally published as a journal article, and I have retained its original structure so that it can continue to be usefully read as a separate stand-alone piece. Conversely, it could conceivably be skipped without losing the continuity of the argument (though surely risking some important insights). Chapter 4 is a key chapter. And in many respects so is chapter 7 (this is where the notion of "entanglement" takes on important nuances, textures, and crucial noncolloquial meanings). Less scientifically inclined readers, or readers who may think of themselves as not very interested in the details of the philosophical issues in quantum physics, may be tempted to skip chapter 7. I would like to encourage at least a cursory reading of this chapter, if only for its valuable insights into the nature of causality, identity, and nature. Unsuspecting readers may find themselves drawn in more than they would have thought. Poststructuralist scholars, in particular, who are used to making their way through difficult and dense theoretical terrains, will not want to skip over the remarkable and radical reworking of some key concepts in their lexicon. Quantum leaps in any case are unavoidable. Whatever the nature of your entangled engagement, I hope you find it enjoyable and thought provoking.

ONE

Meeting the Universe Halfway

Because truths we don't suspect have a hard time
making themselves felt, as when thirteen species
of whiptail lizards composed entirely of females
stay undiscovered due to bias
against such things existing,
we have to meet the universe halfway.
Nothing will unfold for us unless we move toward what
looks to us like nothing: faith is a cascade.
The sky's high solid is anything
but, the sun going under hasn't
budged, and if death divests the self
it's the sole event in nature
that's exactly what it seems.

—ALICE FULTON, "Cascade Experiment"

On the morning after giving an invited lecture on the constructed nature of scientific knowledge, I had the privilege of watching as an STM (scanning tunneling microscope) operator zoomed in on a sample of graphite, and as we approached a scale of thousands of nanometers . . . hundreds of nanometers . . . tens of nanometers . . . down to fractions of a nanometer, individual carbon atoms were imaged before our very eyes. The experience was so sublime that it sent chills through my body—and I stood there, a theoretical physicist who, like most of my kind, rarely ventures into the basements of physics buildings that experimental colleagues call "home," conscious that this was one of those life moments when the amorphous jumble of history seems to crystallize in a single instant. How many times had I recounted for my students the evidence for the existence of atoms? And there they were—just the right size and grouped in a hexagonal structure with the interatomic spacings as predicted by theory. "If only Einstein, Rutherford, Bohr, and especially Mach could have seen this!" I exclaimed. And as the undergraduate students operating the instrument (which they had just gotten to work the day before by carefully eliminating sources of vibrational interference—

we're talking nanometers here) disassembled the chamber that held the sample so that I could see for myself the delicate positioning of the probe above the graphite surface, expertly cleaved with a piece of Scotch tape, I mused aloud that "seeing" atoms will quickly become routine for students (as examining cells with visual-light microscopes, and in turn the structure of molecules by electron microscopes, became routine for earlier generations) and that I was grateful to have been brought up in a scientific era without this particular expectation.[1]

At this point in my story, I imagine there will be scientific colleagues who will wonder whether this presented a moment of intellectual embarrassment for your narrator, who had on the previous night insisted on the constructed nature of scientific knowledge. In fact, although I was profoundly moved by the event I had just witnessed, standing there before the altar of the efficacy of the scientific enterprise, I was unrepentant. For as constructivists have tried to make clear, empirical adequacy is not an argument that can be used to silence charges of constructivism. The fact that scientific knowledge is constructed does not imply that science doesn't "work," and the fact that science "works" does not mean that we have discovered human-independent facts about nature. (Of course, the fact that empirical adequacy is not proof of realism is not the endpoint, but the starting point, for constructivists, who must explain how it is that such constructions work—an obligation that seems all the more urgent in the face of increasingly compelling evidence that the social practice of science is conceptually, methodologically, and epistemologically allied along particular axes of power.)[2]

On the other hand, I stand in sympathy with my scientific colleagues who want science studies scholars to remember that there are cultural *and* natural causes for knowledge claims. While most constructivists go out of their way to attempt to dispel the fears that they are either denying the existence of a human-independent world or the importance of natural, material, or nonhuman factors in the construction of scientific knowledge, the bulk of the attention has been on social or human factors. To be fair, this is where the burden of proof has been placed: constructivists have been responding to the challenge to demonstrate the falsity of the worldview that takes science as the mirror of nature. Nonetheless, as both the range and sophistication of constructivist arguments have grown, the charge that they embrace an equally extreme position—that science mirrors culture—has been levied against them with increasing vigor. While few constructivists actually take such an extreme position, science studies scholars would be remiss in simply dismissing this charge as a trivial oversimplification and misunderstanding of the varied and complex positions that come under the rubric of constructivism. The anxiety being expressed, though admittedly displaced, touches on the legitimate concern about the privileging of epistemological issues over ontological ones in the constructivist literature. Ontological issues have not been totally ignored, but they have not been given sufficient attention.

The ontology of the world is a matter of discovery for the traditional realist. The assumed one-to-one correspondence between scientific theories and reality is used to bolster the further assumption that scientific entities are unmarked by the discoverers: nature is taken to be revealed by, yet independent of, theoretical and experimental practices, that is, transparently given. Acknowledging the importance of Cartwright's (1983) philosophical analysis decoupling these assumptions and her subsequent separation of scientific realism into two independent positions—realism about theories and realism about entities—Hacking (1982), like Cartwright, advocates realism toward entities. Shifting the focus in studies of science away from the traditional emphasis on theory construction to the examination of experimental practice, Hacking grounds his position on the ability of the experimenter to manipulate entities in the laboratory. That which exists is that which we can use to intervene in the world to affect something else: electrons are counted as real because they are effective experimental tools, not because they have been "found." Galison (1987) also centers experimental practice in his historical analysis comparing three different periods of twentieth-century physics experimentation, wherein he generalizes Hacking's criterion for the reality of entities by underlining the importance of the notions of stability and directness.[3] Other approaches go further in interrogating the immediate thereness of nature. Latour (1993) prioritizes stability as well, posing it as one variable of a two-dimensional geometry whose other axis connects the poles of Nature and Society. Essence thus becomes the trajectory of stabilization within this geometry that is meant to characterize the variable ontologies of quasi-objects. In contrast, Haraway (1988) emphasizes instability: it is the instability of boundaries defining objects that is the focal point of her explicit challenge not only to conceptions of nature that claim to be outside of culture, but also to the separation of epistemology from ontology. The instability of boundaries and Haraway's insistence that the objects of knowledge are agents in the production of knowledge feature her notions of cyborgs (1985) and material-semiotic actors (1988), which strike up dissonant and harmonic resonances with Latour's hybrids and quasi-objects (1993). Moving to what some consider the opposite pole of the traditional realist position are the semiotic and deconstructionist positions. To many scientists as well as science studies scholars, the theories of semiotics and deconstruction, which call into question the assumed congruity of signifier and signified, insisting on the intrinsic arbitrariness of the sign or representation, seem to be the ultimate in linguistic narcissism. However, while insisting that we are always already in the "theater of representation," Hayles (1993) takes exception to extreme views that hold that language is groundless play, and while she does not provide us with access to the real, she does attempt to place language in touch with reality by reconceptualizing referentiality. Hayles's theory of constrained constructivism relies on consistency (in opposition to the realist notion of congruence) and the semiotic notion of negativity to acknowledge the importance of constraints offered by a reality that cannot be seen in its positivity: as she puts it, "Although there may be no outside that we can know, *there is a boundary*" (40; italics in original).

These attempts to say something about the ontology of our world are exceptions rather than the rule in the science studies literature.[4] What is needed is a deeper understanding of the ontological dimensions of scientific practice. It is crucial that we understand the technologies by which nature and culture interact. Does nature provide some template that gets filled in by culture in ways that are compatible with local discourses? Or do specific discourses provide the lenses through which we view the layering of culture on nature? Does the full "texture" of nature get through, or is it partially obliterated or distorted in the process? Is reality an amorphous blob that is structured by human discourses and interactions? Or does it have some complicated, irregular shape that is differently sampled by varying frameworks that happen to "fit" in local regions like coincident segments of interlocking puzzle pieces? Or is the geometry fractal, so that it is impossible for theories to match reality even locally? At what level of detail can any such question be answered, if at all? And what would it mean? Is it possible to take any of these questions seriously in the academy in the early twenty-first century? Won't this still sound too much like metaphysics to those of us trained during the various states of decay of positivist culture? And if we don't ask these questions, what will be the consequences? As Donna Haraway reminds us, "What counts as an object is precisely what world history turns out to be about" (1988, 588). I seek some way of trying to understand the nature of nature and the interplay of the material and the discursive, the natural and the cultural, in scientific and other social practices. Consequently I will place considerably more emphasis on ontological issues than

is common in science studies, although I will not ignore the epistemological issues either, since there is good reason to question the traditional Western philosophical belief that ontology and epistemology are distinct concerns.

After articulating a new "ontoepistemological" framework, I will own up to its realist tenor.[5] After a resurgence of interest in scientific realism in the 1980s, its popularity seems to have waned once again, if not because of the death knell sounded by Fine's (1984) clever accounting of the metatheoretical failure of arguments for realism, then at least because of the commonplace tendency on the part of constructivists to present scientific realism as naive, unreflexive, and politically invested in its pretense to an apolitical posture. In fact, the pairing of constructivism with some form of antirealism has become nearly axiomatic: if we acknowledge the cultural specificity of scientific knowledge construction, are we not obligated to relinquish the hope of constructing theories that are true representations of independent reality? For example, in offering a concrete case of the underdetermination thesis, Cushing (1994) argues that the fact that distinctive theories can account for the same empirical evidence means that realists are hard-pressed to make an argument for theoretical access to the actual ontology of our world.[6] For the most part, constructivists have expressed either outright disdain for, or at least suspicion toward, realism and have explicitly adopted antirealist positions, or they have refused the realism-antirealism debate altogether either because they feel limited by this very opposition (see, for example, Fine 1984; Pickering 1994) or because they have thought it more fruitful to focus on other issues. I must confess to having sympathy particularly with the latter positions, but I also think that realism has all too quickly been dismissed. Realism has been invoked to support both oppressive and liberatory positions and projects, and my hope is that at this historical juncture, the weight of realism—the serious business and related responsibility involved in truth hunting—can offer a possible ballast against the persistent positivist scientific and postmodernist cultures that too easily confuse theory with play.[7]

Realizing the multiplicity of meanings that realism connotes, at this juncture I want to clarify how I take realism in the first instance. As a starting point, I follow Cushing's lead:

> I assume, perhaps unreasonably, that a scientific realist believes successful scientific theories to be capable of providing reliable and understandable access to the ontology of the world. If one weakens this demand too much, not much remains, except a belief in the existence of an objective reality to

which we have little access and whose representation by our theories is nebulous beyond meaningful comprehension. In such a situation, is it worth worrying about whether or not one is a realist? (Cushing 1994, 270n26)

Although I will ultimately add substantive qualifications to this definition, I do not intend to weaken what I take to be the spirit of Cushing's demand, and I have therefore selected this starting point to clarify the sense of realism with which I mean to engage, as separate from some other more general uses in the science studies literature, including discussions that oppose realism to relativism, or realism to linguistic monism, or realism to subjectivism. My first concern is not with realism in these senses: I grant that there are forms of antirealism that are not relativist, that do not deny the existence of an extralinguistic reality, and that are compatible with various notions of objectivity. That is, in the spirit of Cushing's query, I want to limit the elasticity of the meaning of realism for my initial purposes. Science studies scholars have labored long and hard to articulate moderate constructivist positions that reject the extremes of objectivist, subjectivist, absolutist, and relativist stances, but it is perhaps inappropriate to label these as realist on just such bases alone. That is, I do not want to turn these accomplishments aside by setting up realism as the foil to the entire family of apparitions, including some that scientists find most haunting. In this regard, it is perhaps important to acknowledge that feminist science studies scholars in particular staunchly oppose epistemological relativism, with an intensity shared by scientists (a fact that may come as a surprise to scientists and others who have not studied the feminist literature), though few have embraced realist positions.[8] Seeing epistemological relativism as the mirror twin of objectivism, and both as attempts to deny the embodiment of knowledge claims, feminist theories of science, including Haraway's theory of situated knowledges (1988), Harding's strong objectivity (1991), Keller's dynamic objectivity (1985), and Longino's contextual empiricism (1990), articulate nonrelativist antirealist positions. Consequently, although my discussion of realism is concerned with the sense in which direct engagement with the ontology of our world is possible, I will also attempt to satisfy the high standards that have already been set by specifying the ways in which the new form of realism that I propose rejects these other extreme oppositions.[9]

I call my proposed ontoepistemological framework "agential realism."[10] (My motivation for using an adjectival form of "agency" as the modifier will be clarified later.) Importantly, agential realism rejects the notion of a correspondence relation between words and things and offers in its stead a causal explanation of how discursive practices are related to material phenomena. It does so by shifting the focus from the nature of representations (scientific and other) to the nature of discursive practices (including technoscientific ones), leaving in its wake the entire irrelevant debate between traditional forms of realism and social constructivism. Crucial to this theoretical framework is a strong commitment to accounting for the material nature of practices and how they come to matter.

THE NATURE OF NATURE AND THE POSSIBILITIES FOR CHANGE

The sciences and science studies are not the only set of (inter)disciplinary practices that have a stake in understanding the nature of nature. Nature's nature has been a central concern of political theorists for centuries. Not only does Aristotle affirm the belief that women and slaves should be assigned subservient social positions by virtue of their allegedly inherent inferior natures, but he posits the very notion of the state—an intrinsically political body—as a natural entity. Arguing against a host of long-standing and newly conceived biological determinist accounts, the renowned feminist philosopher Simone de Beauvoir disarticulates the notions of sex and gender in an effort to dislodge the misguided belief that women's inferior social status is in accord with nature. According to Beauvoir, women in their becoming, as members of the human species, are to be understood as social beings, as transcendental human subjects, constrained, but not determined, by their natures (in contrast to nonhuman creatures who are slaves to their biology).[11]

Like other existentialist political philosophies, Beauvoir's theory of the subject has been strongly criticized for its humanist shortcomings, particularly its reliance on essentialist conceptions of the human and of men and women. Criticisms from feminists and other critical social theorists include a denunciation of Beauvoir's theory for its failure to take account of important structural aspects of the workings of power and its unexamined presuppositions concerning the nature of the category "women" (despite the acknowledgment of its social situatedness). Challenging the notion of the humanist subject as radically free and constituted through self-determination and transparent access to its own consciousness, structuralists argue that the subject is a product of structures—whether of kinship, language, the unconscious, cognitive structures of the mind, or economic, social, and political structures of society—and hence must be understood as an effect rather than a cause. Structuralist accounts of the determination of the subject have been further challenged by poststructuralist approaches, which trouble the idea that there are unitary structures that exist outside, and are determining of, the subject.[12] Rejecting both poles, that subjectivity is either internally generated or externally imposed, poststructuralists eschew not only the very terms of the debates over agency versus structure and free will versus determinism but also the geometrical conception of subjectivity, which would validate "internality" and "externality" as meaningful terms in the debate.[13]

For a range of reasons only hinted at in this brief overview, it is not at all surprising that feminist, poststructuralist, and other critical theorists are deeply interested in the nature of nature.[14] Pressing questions of the nature of embodiment, subjectivity, agency, and futurity hang in the balance. What is at stake is nothing less than the possibilities for change.

FROM REPRESENTATIONALISM TO PERFORMATIVITY

> As long as we stick to things and words we can believe that we are speaking of what we see, that we see what we are speaking of, and that the two are linked.
>
> —GILLES DELEUZE, *Foucault*

> "Words and things" is the entirely serious title of a problem.
>
> —MICHEL FOUCAULT, *The Archaeology of Knowledge*

Liberal social and political theories and theories of scientific knowledge alike owe much to the idea that the world is composed of individuals—presumed to exist before the law, or the discovery of the law—awaiting or inviting representation. The idea that beings exist as individuals with inherent attributes, anterior to their representation, is a metaphysical presupposition that underlies the belief in political, linguistic, and epistemological forms of representationalism. Or to put the point the other way around, representationalism is the belief in the ontological distinction between representations and that which they purport to represent; in particular, that which is represented is held to be independent of all practices of representing. That is, there are assumed to be two distinct and independent kinds of entities—representations and entities to be represented. The system of representation is sometimes explicitly theorized in terms of a tripartite arrangement. For example, in addition to knowledge (i.e., representations), on the one hand, and the known (i.e., that which is purportedly represented), on the other, the existence of a knower (i.e., someone who does the representing) is sometimes made explicit. When this happens, it becomes clear that representations are presumed to serve a mediating function between independently existing entities. This taken-for-granted ontological gap generates questions of the accuracy of representations. For example, does scientific knowledge accurately represent an independently existing reality? Does language accurately represent its referent? Does a given political representative, legal counsel, or piece of legislation accurately represent the interests of the people allegedly represented?

Representationalism has received significant challenge from feminists, poststructuralists, and queer theorists. The names of Michel Foucault and Judith Butler are often associated with such questioning. Butler sums up the problematics of political representationalism as follows:

> Foucault points out that juridical systems of power *produce* the subjects they subsequently come to represent. Juridical notions of power appear to regulate political life in purely negative terms. . . . But the subjects regulated by such structures are, by virtue of being subjected to them, formed, defined, and reproduced in accordance with the requirements of those structures. If this analysis is right, then the juridical formation of language and politics that represents women as "the subject" of feminism is itself a discursive formation and effect of a given version of representationalist politics. And the feminist subject turns out to be discursively constituted by the very political system that is supposed to facilitate its emancipation. (Butler 1990, 2)

In an attempt to remedy this difficulty, critical social theorists struggle to formulate understandings of the possibilities for political intervention that go beyond the framework of representationalism.

The fact that representationalism has come under suspicion in the domain of science studies is less well known, but of no less significance. Critical examination of representationalism did not emerge until the study of science shifted its focus from the nature and production of scientific knowledge to the study of the detailed dynamics of the actual practice of science. This significant shift is one way to coarsely characterize the difference in emphasis between separate disciplinary studies of science (e.g., history of science, philosophy of science, sociology of science) and science studies. This is not to say that all science studies approaches are critical of representationalism; many such studies accept representationalism unquestioningly. For example, countless studies on the nature of scientific representations (including how scientists produce them, interpret them, and otherwise make use of them) take for granted the underlying philosophical viewpoint that gives way to this focus—namely, representationalism.[15] On the other hand, some science studies researchers have made a concerted effort to move beyond representationalism.

Ian Hacking's *Representing and Intervening* (1983) brought the question of the limitations of representationalist thinking about the nature of science to the forefront. The most sustained and thoroughgoing critique of representationalism in the philosophy of science and science studies comes from the philosopher of science Joseph Rouse. Rouse has taken the lead in interrogating the constraints that representationalist thinking places on theorizing the nature of scientific practices.[16] For instance, Rouse (1996) points out that while the hackneyed debate between scientific realism and social constructivism moved frictionlessly from philosophy of science to science studies, these adversarial positions have more in common than their proponents acknowledge. Indeed, they share representationalist assumptions that foster such endless debates: both scientific realists and social constructivists believe that scientific knowledge (in its multiple representational forms such as theoretical concepts, graphs, particle tracks, and photographic images) mediates our access to the material world; where they differ is on the question of referent, whether scientific knowledge represents things in the world as they really are (i.e., nature) or objects that are the product of social activities (i.e., culture), but both groups subscribe to representationalism.

Representationalism is so deeply entrenched within Western culture that it has taken on a common-sense appeal. It seems inescapable, if not downright natural. But representationalism (like "nature itself," not merely our representations of it) has a history. Hacking traces the philosophical problem of representations to Democritus's dream of atoms and the void. According to Hacking's anthropological philosophy, representations were unproblematic before Democritus: "The word 'real' first meant just unqualified likeness" (1983, 142). With Democritus's atomic theory emerges the possibility of a gap between representations and represented—"appearance" makes its first appearance. Is the table a solid mass made of wood or an aggregate of discrete entities moving in the void? Atomism poses the question of which representation is real. The problem of realism in philosophy is a product of the atomistic worldview.

Rouse identifies representationalism as a Cartesian byproduct—a particularly inconspicuous consequence of the Cartesian division between "internal" and "external" that breaks along the line of the knowing subject. Rouse brings to light the asymmetrical faith in word over world that underlines the nature of Cartesian doubt:

> I want to encourage doubt about [the] presumption that representations (that is, their meaning or content) are more accessible to us than the things they supposedly represent. If there is no magic language through which we can unerringly reach out directly to its referents, why should we think there is nevertheless a language that magically enables us to reach out directly to its sense or representational content? The presumption that we can know what we mean, or what our verbal performances say, more readily than we can know the objects those sayings are about is a Cartesian legacy, a linguistic variation on Descartes' insistence that we have a direct and privileged access to the contents of our thoughts which we lack towards the "external" world. (Rouse 1996, 209)

In other words, the asymmetrical faith we place in our access to representations over things is a historically and culturally contingent belief that is part of Western philosophy's legacy and not a logical necessity; that is, it is simply a Cartesian habit of mind. It takes a healthy skepticism toward Cartesian doubt to be able to begin to see an alternative.[17]

It is possible to develop coherent philosophical positions that deny the basic premises of representationalism. A performative understanding of naturalcultural practices is one alternative. *Performative* approaches call into question representationalism's claim that there are representations, on the one hand, and ontologically separate entities awaiting representation, on the other, and focus inquiry on the practices or performances of representing, as well as the productive effects of those practices and the conditions for their efficacy. A performative understanding of scientific practices, for example, takes account of the fact that knowing does not come from standing at a distance and representing but rather from *a direct material engagement with the world*.[18] Importantly, what is at issue is precisely the nature of these enactments. Not any arbitrary conception of doings or performances qualifies as performative. And humans are not the only ones engaged in performative enactments (which are not the same as theatrical performances). A performative account makes an abrupt break from representationalism that requires a rethinking of the nature of a host of fundamental notions such as being, identity, matter, discourse, causality, dynamics, and agency, to name a few. In what follows, I will articulate an understanding of performativity that goes beyond the separate accounts offered by science studies scholars and social and political theorists, incorporating insights from each. Performative accounts in these domains have led parallel lives with surprisingly little exchange between them, thereby reinforcing the perception, which each set of scholars would be quick to reject, that scientific and social and political concerns are separate. I begin by offering some background on each of these separately circulating discourses and then develop my ideas further in the chapters that follow.

REALISM WITHOUT REPRESENTATIONALISM

> We shall count as real what we can use to intervene in the world to affect something else, or what the world can use to affect us.
>
> My attack on scientific antirealism is analogous to Marx's onslaught on the idealism of his day. Both say that the point is not to understand the world but to change it.
>
> —IAN HACKING, *Representing and Intervening*

As late as the end of the nineteenth century, physicists were predominantly antirealists in their attitudes toward atoms. Atoms were thought to be "representative fictions," not bits of matter.[19] Today the situation is very different. Individual atoms are regularly imaged using scanning tunneling microscopes (STM). Moreover, this technology can be used not merely to view individual atoms but to pick them up and move them—one at a time![20]

The philosopher Ian Hacking uses manipulability—that is, the ability to intervene effectively—as the criterion for determining what is real. Hacking claims that whatever individual experimental physicists might believe about whether scientific theories are true accounts of the world or simply useful models for thinking with, it wouldn't make sense for them to be anything but realists toward the entities that they use as tools: "Experimenting on an entity does not commit you to believing that it exists. Only *manipulating* an entity, in order to experiment on something else, need do that. . . . [For example,] electrons are no longer ways of organizing our thoughts or saving the phenomena that have been observed. They are now ways of creating phenomena in some other domain of nature. Electrons are tools" (Hacking 1983, 263). Thus Hacking spells out his criterion as follows: "We shall count as real what we can use to intervene in the world to affect something else, or what the world can use to affect us" (146).

Reflection is insufficient; intervention is key: "Don't just peer, interfere" (189). According to Hacking, our ability to effectively intervene provides the strongest case for realism. In this regard, he makes a distinction between two kinds of realism: realism toward entities, what might be called "ontological realism," and realism toward theories, or "epistemological realism."[21] Hacking subscribes to the former but not the latter: in his account, intervening (i.e., experimenting) rather than representing (i.e., theorizing) is the basis for realism.

Hacking's intervention is particularly noteworthy for its attempt to disentangle realism from its traditional representationalist formulation. Hacking takes issue with the long-standing philosophical tradition that considers theories and representations to be the stuff of science, while experimentation is either completely ignored or seen as an adjunct of theory (which, in this closed account, provides the very lens through which experiments are designed and interpreted). He argues, by contrast, that experimentation should be understood as a complex practice in its own right.

Take the example of microscopy. In Hacking's account, "seeing" atoms or other entities with the aid of a microscope is not a matter of simply looking—of passively gazing on something as a spectator—but an achievement that requires a complex set of practices to accomplish. To "see," one must actively intervene: "You learn to see through a microscope by doing, not just looking" (189). To begin with, obtaining a reliable image free of all artifacts entails experimental know-how, intuition, ingenuity (all three of which are acquired through practice), a good deal of tinkering, the honing of tactile techniques in tune with the specificities of the instrumentation (including any of its idiosyncrasies), learning how to discriminate between unwanted noise and desired signal, between fact and artifact, and all kinds of other non-theory-based manipulations.[22] And part of seeing is also being convinced about what one sees. Hacking argues that if one uses different practices, based on different physical principles (e.g., uses different kinds of microscopes), and winds up seeing the same thing, then one would be hard pressed to explain this coincidence without invoking some kind of conspiracy of unrelated physical processes. And when what we learn how to see using this instrument and its attached set of skills fits with insights from other fields of science, our confidence deepens. "We are convinced not by a high powered deductive theory about the [entity being imaged]—there is none—but because of a large number of interlocking low level generalizations that enable us to control and create phenomena in the microscope" (209).

The STM is a particularly interesting example in this regard. Since it works on a different set of physical principles than optical microscopes, it undermines any illusion that the image represents the mere magnification of what we see with our eyes. In fact, as Hacking correctly notes, optical microscopes don't work like magnifying glasses, either; while the optics of the eye and magnifying glasses can be explained using the principles of geometrical optics (e.g., the laws of refraction), Ernst Abbe's meticulous investigations of the workings of the microscope reveal that the phenomenon of diffraction is central to the workings of the optical microscope. Geometrical optics are not sufficient to account for the microscope's operation; the laws of physical optics must be taken into account. But the STM example makes the difference quite stark.

If we zoom in on the practices of forming an image by means of a scanning tunneling microscope, it becomes crystal clear that it would be a distortion of the facts to liken image formation to taking a picture with a point-and-shoot camera.[23] "Representing" isn't simply a matter of standing back at some distance and opening one's eyes or pushing a button. To the contrary, STM experts like Don Eigler have suggested that image formation using a scanning tunneling microscope is more aptly likened to an encounter that engages the sense of touch rather than sight: the STM, he says, "forms an image in a way which is similar to the way a blind person can form a mental image of an object by feeling the object" (Eigler 1999, 427).[24] As a blind person uses a cane to scan the topography of a landscape, so the STM operating system maneuvers a microscope tip across the surface of the specimen being imaged. (The microscope tip, which is a finely sharpened tungsten wire, terminates in a single atom.) But rather than physically touching the cane to a street surface to scan for bumps or indentations in the road, the STM operates by scanning the surface using a "tunneling current" to "feel" the surface.[25]

"Tunneling," a uniquely quantum mechanical phenomenon, enables particles to traverse energy barriers that should be, at least according to the laws of classical Newtonian physics, impossible to cross.[26] In this case, the particles in question are electrons. The electrons' (quantum mechanical) ability to cross the barrier depends on the distance between the microscope tip and the surface atoms of the sample being measured. When the tip is close enough to the sample surface, the electrons flow across the barrier, forming a small electrical current. The current thus formed between the tip and the surface provides a measure of the detailed structure of the surface.

Here's how it works. A small voltage is applied to the microscope tip. If the tip is then positioned sufficiently close to the surface of the specimen (typically within a few nanometers), a small number of electrons bound to the surface of the specimen (by the electromagnetic force) will tunnel across the gap, thereby forming a very small current between the electron "cloud" of the surface atoms of the specimen and the tip. The amount of current that flows is related to the characteristics of the energy barrier, which is directly

related to the specific arrangement of atoms on the surface. Using a piezoelectric crystal to delicately position the microscope tip a few nanometers above the surface of the specimen, it is possible to scan the tip across it at a very close distance. The measured tunneling current data can then be mapped into an image on a computer screen. In other words, the STM provides an image of the atomic arrangement of a surface by sensing corrugations in the electron "cloud" of the surface atoms of the specimen.[27]

So "seeing" using a scanning tunneling microscope operates on very different physical principles than visual sight. And furthermore, as Hacking would be quick to remind us, "seeing" takes a good deal of practice: the STM operator does not simply insert a specimen and push a button, and voilà, an image appears. The specimen has to be prepared and carefully positioned on the scan head; a new tip has to be cut for each specimen; the tip has to be carefully positioned above the surface of the specimen; the specimen's tilt coordinates have to be adjusted properly; the system has to be isolated from direct light, vibrations, air currents, and temperature fluctuations during the scan, or else the image will be compromised; a scan range must be selected; and the operator must decide if the image produced constitutes a "good image." The separation of fact from artifact depends on the proper execution of each of these steps and requires skill and know-how achieved through experience.

Examples like this make it clear that representationalism is a practice of bracketing out the significance of practices; that is, representationalism marks a failure to take account of the practices through which representations are produced. Images or representations are not snapshots or depictions of what awaits us but rather condensations or traces of multiple practices of engagement. An STM image does not, on its own, make or break our belief in the reality of atoms; it's just one more piece of evidence—a spectacular display, to be sure—in a web of evidence and practices that produce what we take to be evidence.

Hacking's intervention in the realism-antirealism debates turns on his insistence that experimentation is not a theory-laden practice (in the Kuhnian sense) but a complex set of practices in their own right. But granting experimentation its due need not entail leaving theory behind, ensnared in the trap of representationalism. This asymmetry in his conceptualization of experimenting versus theorizing is implicated in his asymmetrical realist stance: realism toward entities, but not theories. But how realistic is Hacking's account of theorizing?

The physicist Niels Bohr takes issue with the notion of theorizing as representing. In Bohr's proto-performative account (which I discuss in detail in chapter 3), theorizing must be understood as an embodied practice, rather than a spectator sport of matching linguistic representations to preexisting things.[28] Concepts, in Bohr's account, are not mere ideations but specific physical arrangements. In the absence of due consideration to this crucial point, Bohr warns that scientists can only speculate about mere abstractions, and in so doing, they fail to provide an objective account of the phenomena they are studying. (Indeed, a failure to correctly identify the objective referent accounts for many of the paradoxical features of quantum theory.)

While Hacking distinguishes between intervening and representing, associating the former with experimental practice and the latter with theory production, I argue that Bohr's proto-performative account suggests that scientific practices may more adequately be understood as a matter of intervening rather than representing, on all counts—that is, with respect to all dimensions of this complex web of practices. Or perhaps "intervening" isn't the appropriate verb for describing the activity at issue, in either case, as we will see.

Ironically, then, Hacking could be accused of making a caricature of theorizing in much the same way that he points out that some philosophers are reductive in their considerations of the complex practice of experimenting. One particularly interesting counterpoint to Hacking's notion of scientific theories is the practice-based account of scientific theorizing offered by Peter Galison, a historian of science, in his study of how Einstein arrived at his special theory of relativity. Galison argues that the theory of special relativity did not hatch full blown from the head of Einstein, the result of a solitary mind occupied with a flurry of *abstract* ideas. Rather, the central idea of clock coordination was an important problem of great *practical* significance in Europe in the early 1900s, and Einstein's seat in the patent office offered him a firsthand view of a multitude of proposed new technological solutions to the problem:

> When Einstein came to the Bern patent office in 1902 he entered into a world in which the triumph of the electrical over the mechanical was already symbolically wired to dreams of modernity. He found a world in which clock coordination was a practical problem (trains, troops, and telegraphs) demanding workable, patentable solutions in exactly his area of greatest concern and professional occupation: precision electromechanical instrumentation. The patent office was anything but a deep-sea lightship. No, the office was a grandstand seat for the great parade of modern technologies. And as coordinated clocks went by, they weren't traveling alone; the network of electrical coordination signified political, cultural, and technical unity all at once. Einstein seized on this new, conventional simultaneity machine and installed it at the principled beginning of his new physics. In a certain sense he had completed the grand time coordination project of the nineteenth century, but by eliminating the master clock and raising the conventionally set time to a physical principle, he had launched a distinctively modern twentieth-century physics of relativity. (Galison 2000, 388–89)

Social, technological, and scientific practices that included the entangled apparatuses of colonial conquest, democracy, world citizenship, antianarchism, trains, telegraphs, clocks, and other electromechanical devices composed of wires and gears all played a role in the production of the special theory of relativity. What was at stake, according to Galison, was "always practical and more than practical, at once material-economic necessity *and* cultural imaginary" (367). Time isn't an abstract idea for Einstein; time is what we measure with a clock. As Bohr argues and Galison's example beautifully illustrates, ideas that make a difference in the world don't fly about free of the weightiness of their material instantiation. To theorize is not to leave the material world behind and enter the domain of pure ideas where the lofty space of the mind makes objective reflection possible. *Theorizing, like experimenting, is a material practice.*

In fact, once theory and experiment are no longer understood in their reified forms but seen as dynamic practices of material engagement with the world, we can see that these sets of practices are complexly entangled in ways that representationalist views of science (which treat theory and experiment as separate domains with one or the other as dominant and primary) elide. Which is not to say that "theorists" and "experimentalists" are trained the same way or engage in the same set of practices, but rather to appreciate the fact that both theorists and experimentalists engage in the intertwined practices of theorizing and experimenting.

Furthermore, despite Hacking's best intentions to leave representationalist beliefs behind, his entity realism takes on board one of representationalism's fundamental metaphysical assumptions: the view that the world is composed of individual entities with separately determinate properties. Indeed, most forms of realism presuppose a metaphysics that takes for granted the existence of individual entities, each with its own roster of nonrelational properties.[29] As such, realism is often saddled with essentialism. But realism need not subscribe to an individualist metaphysics or any other representationalist tenet (indeed, I would argue that any realist account worth its salt should not endorse such idealist or magical beliefs). Realness does not necessarily imply "thingness": what's real may not be an essence, an entity, or an independently existing object with inherent attributes. The assumption of thingness remains in place at the base of Hacking's entity realism: words and things are still the order of the day.

Like Hacking I am interested in a nonrepresentationalist realist account of scientific practices that takes the material nature of practices seriously. Not Hacking's realism toward entities, but rather realism toward *phenomena* and the entangled material practices of knowing and becoming. *Phenomena*, according to my agential realist account, are neither individual entities nor mental impressions, but entangled material agencies (to be discussed more fully below).[30] The agential realist understanding that I propose is a nonrepresentationalist form of realism that is based on an ontology that does not take for granted the existence of "words" and "things" and an epistemology that does not subscribe to a notion of truth based on their correct correspondence. Agential realism offers the following elaboration of Hacking's critique of representationalism: *experimenting and theorizing are dynamic practices that play a constitutive role in the production of objects and subjects and matter and meaning.*[31] As I will explain, theorizing and experimenting are not about *intervening* (from outside) but about *intra-acting* from within, and as part of, the phenomena produced.[32] Agential realism is explicated in chapter 4 and subsequent chapters; for now, I want to return to the question of metaphysics.

Importantly, it is precisely on this same point that one encounters in crossing the threshold between representationalism and performativism—namely, the metaphysics of individualism—that many other science studies approaches stumble as well, although the issue that they trip over is often quite different. Like Hacking, most science studies scholars are not apt to take the objects of scientific practices for granted; rather, they too are interested in investigating the details of the laboratory practices that produce them. Unlike Hacking, however, actor network theorists, among others, have disassembled the belief that what scientists make evident through their practices is the existence of discrete objects; on the contrary, they have emphasized that the efficacy of the scientific endeavor depends on specific procedures for making networks or assemblages of humans and nonhumans. That is, "things" (in the traditional sense) are surely not the order of the day.[33] Ironically, however, mainstream science studies approaches, and

even some feminist science studies approaches, take it as a given that social variables like gender, race, nationality, class, and sexuality are properties of individual persons, thereby reinstalling the metaphysics of individualism. The taken-for-granted object-nature of things gets dislodged, but questions related to discursive practices—especially those Foucault would consider to be at the crux of the discourse-power-knowledge nexus, such as the discursive constitution of the subject—are neglected. Lest this important point be misunderstood in a particularly ironic fashion, it is perhaps worth emphasizing that this is *not* to say that subject production is all about language—indeed, that's precisely Foucault's point in moving away from questions of linguistic representation and focusing instead on the constitutive aspects of discursive practices in their materiality.

Building on Foucault's critique of representationalism, Judith Butler's influential theory of gender performativity theorizes the gendered constitution of the subject. As Butler emphasizes, gender is not an attribute of individuals. Rather, gender is a doing, not in the sense that there is a pregendered person who performs its gender, but rather with the understanding that *gendering* "is, among other things, the differentiating relations by which . . . subjects come into being" and "the matrix through which all willing first becomes possible" (1993, 7). Gendering, Butler argues, is a temporal process that operates through the reiteration of norms.[34] In other words, Butler is saying that gender is not an inherent feature of individuals, some core essence that is variously expressed through acts, gestures, and enactments, but an iterated doing through which subjects come into being. But these are precisely the kinds of points that one would think that actor network theorists and other scholars attuned to looking for ways in which "objects" emerge through scientific practices would be especially attentive to. And yet there has been surprisingly little cross-pollination between feminist poststructuralist theory and science studies.[35] Even in the feminist science studies literature, one is hard pressed to find other direct engagements with Butler's work on performativity.

Science studies approaches that fail to take these insights into account are not simply setting aside a variable or two that can easily be added into analyses at a later date; rather, they make the same kind of mistake as the representationalist approaches they reject—they fail to take account of the constitutive nature of practices. Indeed, as Butler and Bohr emphasize, that which is excluded in the enactment of knowledge-discourse-power practices plays a *constitutive* role in the production of phenomena—exclusions matter both to bodies that come to matter and those excluded from mattering.

Crucially, there are epistemological, ontological, and ethical issues at stake. This applies both to the practices that are being observed (e.g., laboratory practices) and to the knowledge-making practices that contribute to the science studies literature. But the mere acknowledgment of the fact that science studies scholars are actors involved in performing their own set of practices doesn't go nearly far enough. Turning the mirror back on oneself is not the issue, and reflexivity cannot serve as a corrective here. Rather, the point is that these *entangled practices* are productive, and who and what are excluded through these entangled practices matter: different intra-actions produce different phenomena.[36] Or so I will argue, but I am jumping ahead of myself here. The point is this: one can't simply bracket (or ignore) certain issues without taking responsibility and being accountable for the constitutive effects of these exclusions. Since science studies needs to take account of gender and other crucial social variables (for the sake of consistency, at the very least), and since it no doubt wants to avoid reinstalling the metaphysics of individualism or other representationalist remnants into its theories, its methods, and its results, turning to performative accounts of gender to find out what they have to offer at least seems like a good place to start.

I want to emphasize in the strongest terms possible that it would be a mistake to think that the main point is simply a question of whether or not gender, race, sexuality, and other social variables are included in one's analysis. The issue is not simply a matter of inclusion. The main point has to do with power. How is power understood? How are the social and the political theorized? Some science studies researchers are endorsing Bruno Latour's proposal for a new parliamentary governmental structure that invites nonhumans as well as humans, but what, if anything, does this proposal do to address the kinds of concerns that feminist, queer, postcolonial, (post-)-Marxist, and critical race theorists and activists have brought to the table?[37] Nonhumans are in, but the concerns of this motley crew of theorists and activists seem not to have been heard, let alone taken into account. Indeed, their presence has barely been acknowledged. Not that they/we are standing in line waiting to be granted entrance into the Halls of Power.

In his book *Politics of Nature*, Bruno Latour deftly exposes the modernist constitution for its illicit bicameral assemblies—the House of Sciences, which claims to represent things as they are, and the House of Politics, which claims to represent humans' concerns—and the faulty notions of representation they evoke. I couldn't agree more that the old bicameralism that splits the governmental houses into separate powers, with nature on one side and the social on the other, is broken. But it can't simply be repaired by making a new bicameralism—a new *representationalist* form of government. The political field is not limited to the statehouse. And representationalist governments have a long history of shoring up their "own" borders while raiding and ravaging other lands. What conception of power, what model of citizenship, what immigration policy is being enacted when a new representationalist democracy is being proposed that only acknowledges two kinds of citizens and their offspring—the fully human (those who had already been granted citizenship) and the fully nonhuman and their hybrids? Haraway (1985) long ago emphasized that this would not be sufficient: cyborg politics are not merely about the cross between human and machine but also about the technobiopolitics of the differentially human and their motley kin. As Butler puts it: "It is not enough to claim that human subjects are constructed, for the construction of the human is a differential operation that produces the more and the less 'human,' the inhuman, the humanly unthinkable" (1993, 8). Any proposal for a new political collective must take account of not merely the practices that produce distinctions between the human and the nonhuman but *the practices through which their differential constitution is produced*. All the efforts to unseat epistemological representationalism (of the House of Science) will be undercut if the political and social field is theorized (yet again) in terms of political and linguistic forms of representationalism. Representationalism (with its metaphysics of individualism) will simply be reinstalled as the order of the day. This is one reason why science studies cannot afford to ignore the insights that our best political and social theorists have to offer.[38]

Poststructuralism offers a notable alternative to representationalism. Poststructuralism is not just some high-tech toy that humanities scholars use to entertain themselves. Poststructuralist approaches aim to take seriously the concerns of the "motley crew," while offering alternative understandings of power and subject formation (displacing the modernist obsession with the representationalist problematic), while furthermore including an examination of the *constitutive* effect of exclusions.

PERFORMATIVITY AND SOCIAL AND POLITICAL AGENCY

Nature has a history, and not merely a social one.

—JUDITH BUTLER, *Bodies That Matter*

The search for alternatives to social constructivism has prompted performative approaches to the study of social, political, economic, and cultural phenomena. Judith Butler's theory of gender performativity has been enormously influential, opening up a range of different investigations into the practices that produce subjects and identities.[39] Performative approaches to questions of race, the economy, and transnational politics are increasingly prevalent. "Performativity" has become a ubiquitous term in literary studies, theater studies, and the nascent inter-interdisciplinary area of performance studies as well. Theorists who adopt performative approaches are often quick to point out that performativity is not the same as performance, and to merely talk of performance does not necessarily make an approach *performative*.

In her groundbreaking and influential book *Gender Trouble*, Butler problematizes the social constructivist model that figures gender as a cultural inscription on the naturally sexed body. To assume that the body is a mute substance, a passive blank slate on which history or culture makes the mark of gender, is to deprive matter of its own historicity, to limit the possibilities for agency, and to instate the sex-gender distinction not simply in terms of the problematic nature-culture dualism but *as* this very distinction.

Butler draws on Foucault's seminal study of the history of sexuality in troubling the very nature of "sex": "For what is 'sex' anyway? Is it natural, anatomical, chromosomal, or hormonal, and how is a feminist critic to assess the scientific discourses which purport to establish such 'facts' for us?" (Butler 1990, 6–7).[40] Foucault's genealogy of sex exposes the fact that the category of sex is a mechanism for unifying an otherwise discontinuous set of elements and functions in the service of the social regulation and control of sexuality, which is effected through the concealment of this construction and the presentation of sex as a bodily given. As Butler notes:

> Not only is the gathering of attributes under the category of sex suspect, but so is the very discrimination of the "features" themselves. That penis, vagina, breasts, and so forth, are *named* sexual parts is both a restriction of the erogenous body to those parts and a fragmentation of the body as a whole. Indeed, the "unity" imposed upon the body by the category of sex is a "disunity," a fragmentation and compartmentalization, and a reduction of erotogeneity. (Butler 1990, 114)

Given this artificial suturing of otherwise disparate features and functions, it is perhaps not surprising that the attempt to provide a determinate scientific test for "the truth of sex" reveals more about the indeterminate nature of sex, and the nature of the practices that seek to quash the indeterminacies intrinsic to this disparate unity, than the mere disclosure of its failure might otherwise seem to suggest. Butler examines the work of a group of molecular biologists who identify TDF (testis-determining factor)

as "*the* binary switch upon which hinges all sexually dimorphic characteristics."[41] For their study, the researchers chose individuals who "were far from unambiguous in their anatomical and reproductive constitutions," including XX-males and XY-females. But the question arises then as to how these very determinations are made when it is precisely this question that is at issue. Relying on external genitalia for this determination seems to root particular ideas about sexuality into the foundations of a study that seeks to investigate the very nature of sex. The researchers also reduce the notion of sex determination to one of male determination to one of testis determination, revealing a set of gendered assumptions at work that enable this conflation. On the basis of these and other considerations, Butler concludes that

> cultural assumptions regarding the relative status of men and women and the binary relation of gender itself frame and focus the research into sex-determination. The task of distinguishing sex from gender becomes all the more difficult once we understand that gendered meanings frame the hypothesis and the reasoning of those biomedical inquiries that seek to establish "sex" for us as it is prior to the cultural meanings that it acquires. (1990, 109)

But if the very notion of a "sexed nature" or "a natural sex" turns out to be "produced and established *as* 'prediscursive,' " that is, is made to pose as that which is prior to culture, as "a politically neutral surface *on which* culture acts," then gender is not the cultural interpretation of sex but "the very apparatus of production whereby the sexes themselves are established" (1990, 7). But is this to suggest that it's gender all the way down? Does culture replace nature? And if so, what happens to the body? Where does the question of matter figure in? For Butler, these reflections do *not* serve as a basis for denying the body its materiality; on the contrary, they reveal the inadequacies of the inscription model of social constructivism.

Indeed, Butler is not out to deny the materiality of the body whatsoever. On the contrary, she proposes "a return to the notion of matter," as we will see hereafter. This "return" to matter is not a simple going back to the notion that matter is the given, that which is already there. It is, however, crucial to Butler's project, for what is at stake is the very nature of change. Butler's intervention calls into question not only the sex-gender binary, which has been foundational to a good deal of feminist theory and gender analysis, but also the nature of agency that is entailed in the inscription model of construction: "When feminist theorists claim that gender is the cultural interpretation of sex or that gender is culturally constructed, what is the manner or mechanism of this construction? If gender is constructed, could it be constructed differently, or does its constructedness imply some form of social determinism, foreclosing the possibility of agency and transformation?" (1990, 7). As Butler notes, the "controversy over the meaning of *construction* appears to founder on the conventional philosophical polarity between free will and determinism" (8). She promptly rejects both options, indeed the very binary conception of causality, and insists that what is needed is a radical rethinking of the nature of identity.

Butler proposes that we understand identity not as an essence but as a doing. In particular, she suggests that gender is not an attribute or essential property of subjects but "a kind of becoming or activity . . . an incessant and repeated action of some sort" (Butler 1990, 112). Butler cautions that this claim—that gender is performed—is *not* to be understood as a kind of theatrical performance conducted by a willful subject who would choose its gender. Such a misreading ironically reintroduces the liberal humanist subject onto the scene, thereby undercutting poststructuralism's antihumanism, which refuses the presumed givenness of the subject and seeks to attend to its production. Crucially, the performative "is not a singular act used by an already established subject, but one of the powerful and insidious ways in which subjects are called into social being from diffuse social quarters, inaugurated into sociality by a variety of diffuse and powerful interpellations" (Butler 1997a, 160). As Butler explains, "the 'I' neither precedes nor follows the process of this gendering, but emerges only within and as the matrix of gender relations themselves" (1993, 7). That is, gender performativity constitutes (but does not fully determine) the gendered subject. Butler's refusal to embrace the binary conception of agency versus structure is evident here. In an effort to avoid problematic conceptions of agency and power embedded in a host of different approaches to subject formation, Butler draws on Foucault's poststructuralist rendering of regulatory power and discursive practices to understand the gendered formation of the subject.

Writing against the competing philosophical paradigms of structuralism and phenomenology (and hermeneutics in its phenomenological influences), Foucault rejects both the idea that subjects are the mere effects of external structures of intelligibility located in large-scale social systems and the idea that reality is an internal product of human consciousness. That is, Foucault refuses the humanist assumption that presumes the existence of an autonomous subject that stands before discourse-power-knowledge practices; on the contrary, Foucault is interested in analyzing the historical conditions that call forth certain kinds of subjectivity. At the same time, he also

rejects structuralist accounts of the production of the subject via the imposition of an external system of Power, Language, or Culture. In particular, Foucault eschews Marxist treatments of ideology and false consciousness as well as humanist accounts that make reference to the intentionality of a unified subject, giving power an interior location within the consciousness of a subject whose interests are taken to be self-transparent. Indeed, Foucault cuts through the agency-structure dualism held in place by the clash between phenomenology and structuralism. In Foucault's account, power is not the familiar conception of an external force that acts on a preexisting subject, but rather an immanent set of force relations that constitutes (but does not fully determine) the subject.[42]

Foucault's analytic of power links discursive practices to the materiality of the body. In *Discipline and Punish*, Foucault argues that the body's materiality is regulated through the movements it exercises. In particular, it is through the repetition of specified bodily acts that bodies are reworked and that power takes hold of the body. Foucault claims that the specific material configuration of the prison (e.g., the Panopticon form) supports and enacts particular discursive practices of punishment. It is crucial to understand that in Foucault's account discursive practices are not the same thing as speech acts or linguistic statements. Discursive practices are the material conditions that define what counts as meaningful statements. However, Foucault is not clear about the material nature of discursive practices. In fact, criticism of Foucault's analytics of power and his theory of discourse often centers on his failure to theorize the relationship between discursive and nondiscursive practices. The closest that Foucault comes to explicating this crucial relationship between discursive and nondiscursive practices is through his notion of *dispositif*, usually translated as *apparatus*. Foucault explains that dispositif is "a thoroughly heterogeneous ensemble consisting of discourses, institutions, architectural forms, regulatory decisions, laws, administrative measures, scientific statements, philosophical, moral and philanthropic propositions—in short, the said as much as the unsaid" (Foucault 1980, 194). But this list does not constitute a positive statement about the relationship between the "said and the unsaid."

Butler draws on Foucault's suggestion that the repetition of regulatory practices produces a specific materialization of bodies to link her notion of gender performativity to the materialization of sexed bodies. In particular, Butler reads the "iterative citationality" of performativity in terms of this repetition, thereby linking the question of identity with the materiality of the body, but not as the cultural inscription model would have it. Significantly, Butler proposes "a return to the notion of matter" in place of the flawed conceptions of construction that circulate in feminist theory and elsewhere, not as site or surface (as in the inscription model) but as "*a process of materialization that stabilizes over time to produce the effect of boundary, fixity, and surface we call matter*" (1993, 9). Not surprisingly, what is at stake in this dynamic conception of matter is an unsettling of nature's presumed fixity and hence an opening up of the possibilities for change. Butler further extends Foucault's analysis of the formation of subjects and bodies by attending to the constitutive exclusions that regulatory practices enact: "Foucault's effort to work the notions of discourse and materiality through one another fail to account for not only what is excluded from the economies of discursive intelligibility that he describes, but *what has to be excluded* for those economies to function as self-sustaining systems" (Butler 1993, 35; italics mine). The constitutive outside marks the limits to discourse. Butler emphasizes that the existence of a constitutive outside thus marks the divergence of her theory from social constructivism: there is indeed an outside to discourse, but not an absolute outside. (She thereby eschews the tired social constructivism versus essentialism debates.) The constitutive outside plays a crucial role in Butler's formulation of the notion of agency.

However, despite these crucial elaborations, it is not at all clear that Butler succeeds in bringing the discursive and the material into closer proximity. The gap that remains in Foucault's theory seems to leave a question mark on Butler's ability to spell out how it is that "the reiterative and citational practice by which discourse produces the effects that it names" can account for the matter of sexed bodies (1993, 2). Questions about the material nature of discursive practices seem to hang in the air like the persistent smile of the Cheshire cat.

If discursive practices constitute a productive social or cultural field, then how much of the very matter of bodies, both human and nonhuman, can be accounted for? Is the matter of things completely social in nature? Are we to understand matter as a purely cultural phenomenon, the end result of human activity? And if so, is this not yet another reenactment of the crossing out of nature by culture? And if not, then how can we explain what nature is in relation to this cultural field? Are there significant ways in which matter matters to the very process of materialization? In other words, while Butler correctly calls for the recognition of matter's historicity, ironically, she seems to assume that it is ultimately derived (yet again) from the agency of language or culture. She fails to recognize matter's dynamism.[43]

This is a crucial point that I want to belabor a bit further. If Foucault, in

queering Marx, positions the body as the locus of productive forces, the site where the large-scale organization of power links up with local practices, then it would seem that any robust theory of the materialization of bodies would necessarily take account of *how the body's materiality* (including, for example, its anatomy and physiology) *and other material forces as well* (including nonhuman ones) *actively matter to the processes of materialization*. As Foucault makes crystal clear in the last chapter of *The History of Sexuality, Volume I*, he is not out to deny the relevance of the physical body; on the contrary, he aims to

> show how the deployments of power are directly connected to the body—to bodies, functions, physiological processes, sensations, and pleasures; far from the body having to be effaced, what is needed is to make it visible through an analysis in which the biological and the historical are not consecutive to one another . . . but are bound together in an increasingly complex fashion in accordance with the development of the modern technologies of power that take life as their objective. Hence, I do not envision a "history of mentalities" that would take account of bodies only through the manner in which they have been perceived and given meaning and value; but a "history of bodies" and the manner in which what is most material and most vital in them has been invested. (Foucault 1978, 151–52)

On the other hand, Foucault does not tell us in what way the biological and the historical are "bound together" such that one is not consecutive to the other. What is it about the materiality of bodies that makes it susceptible to the enactment of the intertwined forces of biology and history? To what degree does the matter of bodies have its own historicity? Are social forces the only ones susceptible to change? If biological forces are in some sense always already historical ones, could it be that there is also some important sense in which historical forces are always already biological? (What would it mean to even ask such a question given the strong social constructivist undercurrent in certain interdisciplinary circles in the early twenty-first century?) For all of Foucault's emphasis on the political anatomy of disciplinary power, he fails to offer an account of the body's historicity in which its very materiality plays an *active* role in the workings of power. This implicit reinscription of matter's passivity is a mark of extant elements of representationalism that haunt his largely postrepresentationalist account.[44] But this is not its only limitation. As Haraway (1997) correctly points out, Foucault's notion of the biopolitical field is seriously outdated and incapable of taking account of the new technoscientific practices that continually rework the boundaries between the "human" and the "nonhuman."

Crucial to understanding the workings of power is an understanding of the nature of power in the fullness of its materiality. To restrict power's productivity to the limited domain of the social, for example, or to figure matter as merely an end product rather than an active factor in further materializations is to cheat matter out of the fullness of its capacity. How might we understand not only how human bodily contours are constituted through psychic processes but also how even the very atoms that make up the biological body come to matter, and more generally how matter makes itself felt? It is difficult to imagine how psychic and sociohistorical forces alone could account for the production of matter. Surely it is the case—even when the focus is restricted to the materiality of "human" bodies (and how can we stop there?)—that there are "natural," not merely "social," forces that matter. Indeed, there is a host of material-discursive forces—including ones that get labeled "social," "cultural," "psychic," "economic," "natural," "physical," "biological," "geopolitical," and "geological"—that may be important to particular (entangled) processes of materialization.[45]

What is needed is a robust account of the materialization of *all* bodies—"human" and "nonhuman"—including the agential contributions of all material forces (both "social" and "natural"). This will require an understanding of the nature of the relationship between discursive practices and material phenomena; an accounting of "nonhuman" as well as "human" forms of agency; and an understanding of the precise causal nature of productive practices that take account of the fullness of matter's implication in its ongoing historicity.[46] (Notice that the notion of a "causal" account need not entail singular causes or linear relationships or even postulate causes separable from their effects.) My proposed contributions toward the development of such a robust understanding include a new account of matter's dynamism, the nature of causality, and the space of agency, as well as a *posthumanist* elaboration of the notion of performativity. My posthumanist account calls into question the givenness of the differential categories of human and nonhuman, examining the practices through which these differential boundaries are stabilized and destabilized.[47] Relatedly, agential realism does not merely offer a unified theory of cultural and natural forces but inquires into the very practices through which they are differentiated.

AGENTIAL REALISM AND QUANTUM PHYSICS

An important inspiration for agential realism comes from my reading of Niels Bohr's philosophy-physics. (I use this hyphenated structure, instead of the usual "philosophy of physics," to emphasize Bohr's unwillingness to think of these interests as distinctive in any sense, contrary to the sharp disciplinary boundaries that are important to contemporary physics culture [Barad 1995].) Bohr's philosophy-physics is a particularly apt starting point for thinking the natural and social worlds together and gaining some important clues about how to theorize the nature of the relationship between them because Bohr's investigations of quantum physics opened up questions not only about the nature of nature but about the nature of scientific and other social practices. In particular, Bohr's naturalist commitment to understanding both the nature of nature and the nature of science according to what our best scientific theories tell us led him to what he took to be the heart of the lesson of quantum physics: *we are a part of that nature that we seek to understand.*

Bohr starts with a critical examination of measurement processes. Measurement is a meeting of the "natural" and the "social." It is a potent moment in the construction of scientific knowledge—it is an instance where matter and meaning meet in a very literal sense. This is one reason why science studies scholars have been interested in studying the role of detectors (in high energy physics)—they are sites for making meaning (Traweek 1988; Galison 1987; Pickering 1984). Significantly, in contrast to the inconsequential role that measurement plays in Newtonian physics, Bohr argues that quantum physics requires a new logical framework that understands the constitutive role of measurement processes in the construction of knowledge. I argue that much like the poststructuralist theories mentioned earlier, which are also centrally concerned with the relationship between matter and meaning, Bohr's new framework moves beyond representationalism and proposes a rich and complex proto-performative account in its stead.

Now, I am quite aware that the ubiquitous appropriation of quantum theory makes it dangerous material to handle these days, and the addition of feminist theory to my list of concerns seems to be quite enough to detonate the explosive mixture, so a few preliminary words of caution may be in order. In a sense, to accomplish my task, I need to "rescue" quantum theory from the problematic discourses of both its overzealous advocates and its unreflective practitioners. In the popular literature, quantum physics is often positioned as the scientific path leading out of the West to the metaphysical Edenic garden of Eastern mysticism. Paralleling these popular renditions, one can find suggestions in the literature that quantum physics is inherently less androcentric, less Eurocentric, more feminine, more postmodern, and generally less regressive than the masculinist and imperializing tendencies found in Newtonian physics. But those who naively embrace quantum physics as some exotic Other that will save our weary Western souls forget too quickly that quantum physics underlies the workings of the A-bomb, that particle physics (which relies on quantum theory) is the ultimate manifestation of the tendency toward scientific reductionism, and that quantum theory in all its applications continues to be the purview of a small group of primarily Western-trained males. It is not my intention to contribute to the romanticizing or mysticizing of quantum theory. On the contrary, as a physicist, I am interested in engaging in a rigorous dialogue about particular aspects of specific discourses on quantum physics and their implications. Hence the reader will not find any claims here to the effect that Niels Bohr is an unappreciated or closet feminist, or that his theory is inherently feminist. Nor is my aim to critique physics by holding it up to some fixed notion of gender. On the contrary, the analysis I present here calls into question notions of identity, agency, and causality that are presumed by such critiques.

On the other hand, I part company with my physics colleagues with neopositivist leanings who believe that philosophical concerns are superfluous to the real subject matter of physics. Rather, I am sympathetic to Bohr's view that philosophy is integral to physics. Indeed, Einstein felt much the same way and once quipped: "Of course, every theory is true, provided you suitably associate its symbols with observed quantities." In other words, physics without philosophy can only be a meaningless exercise in the manipulation of symbols and things, much the same as philosophy without any understanding of the physical world can only be an exercise in making meaning about symbols and things that have no basis in the world. This is why Einstein and Bohr engaged with all their passions about the meaning of quantum theory. Their long-standing debate on the topic is legendary. For the most part, however, the physics community turned its gaze toward more "practical" matters.

Niels Bohr's "philosophical" writings span a period of approximately four decades. Bohr is considered to be (one of) the primary author(s) of the so-called Copenhagen interpretation of quantum mechanics.[48] Although alternative interpretations have been advanced since the formulation of the quantum theory in 1925, from the late 1920s onward the physics community has claimed allegiance to the Copenhagen interpretation.[49] In point of fact, the vast majority of physicists treat the interpretative issues as though they were "merely philosophical," preferring to focus instead on the powerful tools that the quantum formalism provides for purposes of calculation. This particular circumscription of what constitutes "physics" versus what constitutes "philosophy" has exacted a substantial cost for the physics community: the foundational issues of this fundamental physical theory remain unresolved, decades after its founding, and the culture of physics is such

that unreflective (read "pragmatic" or "antiphilosophical") attitudes and approaches are rewarded, despite the fact that there are good reasons to believe that persistent difficulties in the fields of cosmology, quantum gravity, and quantum field theory are derivative of these unresolved issues.[50] The simultaneous centrality and marginality of Bohr's views is also particularly interesting: on the one hand, he was a hero, a leader of the physics community; on the other hand, he was too "philosophical" in his approach to physics.[51]

Bohr often makes reference to the epistemological lessons of quantum theory, and he sees the framework that he offers for quantum physics as having general relevance beyond physics (Folse 1985). There has been a substantial amount of interest in the larger philosophical implications of Bohr's philosophy-physics. Many such investigations leave the interpretative issues in the foundations of quantum theory aside. My interest, however, is not only in the larger philosophical implications. My approach will be to draw out the specifics of a consistent Bohrian framework, grounding the analysis in the physics, and further elaborating Bohr's approach, making explicit implicit ontological dimensions of his account. Once this elaboration is in hand, I return to the interpretative questions in the foundations of quantum theory.[52]

The first task is necessary because there is much disagreement in the secondary literature about how to interpret Bohr. For example, Bohr has been called a positivist, an idealist, an instrumentalist, a (macro)phenomenalist, an operationalist, a pragmatist, a (neo-)Kantian, and a realist by various authors. One of the difficulties in assigning a traditional label to Bohr's interpretative framework is the fact that Bohr is not specific about his ontological commitments. To fill this crucial gap, I propose an ontology that I believe to be consistent with Bohr's views, although I make no claim that this is what he necessarily had in mind. That is, my primary goal is to develop a coherent framework. I try to make sense of the ontological issues on the basis of what Bohr tells us, but I am less interested in trying to figure out what Bohr was "actually" thinking than what makes sense for developing a coherent account. My approach, therefore, is to use Bohr's writings for thinking about these issues, but I do not take them as scripture.[53] Using this analysis of Bohr's philosophy-physics as inspiration, I introduce agential realism as a framework that attends to both the epistemological and ontological issues.

I then offer some examples of applications of agential realism. I consider some specific issues of interest to researchers in the fields of critical social theory, social and political philosophy, feminist theory, queer theory, political economy, physics, philosophy of physics, ethics, epistemology, science studies, and others. I diverge from Bohr in strategy here, but not in spirit. Bohr's methodological approach was to draw out the epistemological lessons of quantum theory for other fields of knowledge by essentially trying to guess what the relevant complementary variables would be in each arena. This analogical strategy often failed, both because he proposed a set of variables that turned out not to be complementary, and because the implications drawn on this basis watered down the complexity and richness of the "epistemological lessons."[54] By contrast, my approach will be to examine specific implications by directly taking on a different set of epistemological and ontological commitments. That is, I will not use the notion of complementarity as a springboard; instead I directly interrogate particular philosophical background assumptions that underlie specific concerns.

Finally, I want to emphasize and make explicit the distinction between my approach and a host of analogical (mis)appropriations of quantum theory that are more common in the literature than physicists (including this one) would wish. I will not put forward any argument to the effect that the quantum theory of the micro world is analogous to situations that interest us in the macro world—be they political, spiritual, psychological, or even those encountered in science studies. My focus is on the development of widely applicable epistemological and ontological issues that can be usefully investigated by a rigorous examination of implicit background assumptions in specific fields. To ask whether it is not suspect to apply arguments made specifically for microscopic entities to the macroscopic world is, in this case, to mistake the approach as analogical. The epistemological and ontological issues are not circumscribed by the size of Planck's constant.[55] That is, I am interested not in mere analogies but in the widely applicable philosophical issues such as the conditions for objectivity, the appropriate referent for empirical attributes, the role of natural as well as cultural factors in technoscientific and other social practices, the nature of bodies and identities, and the efficacy of science.

TWO

Diffractions: Differences, Contingencies, and Entanglements That Matter

> Reflexivity has been recommended as a critical practice, but my suspicion is that reflexivity, like reflection, only displaces the same elsewhere, setting up worries about copy and original and the search for the authentic and really real. . . . What we need is to make a difference in material-semiotic apparatuses, to diffract the rays of technoscience so that we get more promising interference patterns on the recording films of our lives and bodies. Diffraction is an optical metaphor for the effort to make a difference in the world. . . . Diffraction patterns record the history of interaction, interference, reinforcement, difference. Diffraction is about heterogeneous history, not about originals. Unlike reflections, diffractions do not displace the same elsewhere, in more or less distorted form. . . . Rather, diffraction can be a metaphor for another kind of critical consciousness at the end of this rather painful Christian millennium, one committed to making a difference and not to repeating the Sacred Image of Same. . . . Diffraction is a narrative, graphic, psychological, spiritual, and political technology for making consequential meanings.
>
> —DONNA HARAWAY,
> *Modest_Witness@Second_Millennium.FemaleMan©_Meets_OncoMouse™*

The phenomenon of diffraction is an apt overarching trope for this book. Diffraction is a physical phenomenon that lies at the center of some key discussions in physics and the philosophy of physics, with profound implications for many important issues discussed in this book. Diffraction is also an apt metaphor for describing the methodological approach that I use of reading insights through one another in attending to and responding to the details and specificities of relations of difference and how they matter.

As Donna Haraway suggests, diffraction can serve as a useful counterpoint to reflection: both are optical phenomena, but whereas the metaphor of reflection reflects the themes of mirroring and sameness, diffraction is marked by patterns of difference. Haraway focuses our attention on this figurative distinction to highlight important difficulties with the notion of theory, social and political philosophy, feminist theory, queer theory, political economy, physics, philosophy of physics, ethics, epistemology, science studies, and others. I diverge from Bohr in strategy here, but not in spirit. Bohr's methodological approach was to draw out the epistemological lessons of quantum theory for other fields of knowledge by essentially trying to guess what the relevant complementary variables would be in each arena. This analogical strategy often failed, both because he proposed a set of variables that turned out not to be complementary, and because the implications drawn on this basis watered down the complexity and richness of the "epistemological lessons."[54] By contrast, my approach will be to examine specific implications by directly taking on a different set of epistemological and ontological commitments. That is, I will not use the notion of complementarity as a springboard; instead I directly interrogate particular philosophical background assumptions that underlie specific concerns.

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As Donna Haraway suggests, diffraction can serve as a useful counterpoint to reflection: both are optical phenomena, but whereas the metaphor of reflection reflects the themes of mirroring and sameness, diffraction is marked by patterns of difference. Haraway focuses our attention on this figurative distinction to highlight important difficulties with the notion of reflection as a pervasive trope for knowing, as well as related difficulties with the parallel notion of reflexivity as a method or theory (in the social sciences) of self-accounting, of taking account of the effect of the theory or the researcher on the investigation.[1] Haraway's point is that the methodology of reflexivity mirrors the geometrical optics of reflection, and that for all of the recent emphasis on reflexivity as a critical method of self-positioning it remains caught up in geometries of sameness; by contrast, diffractions are attuned to differences—differences that our knowledge-making practices make and the effects they have on the world. Like the feminist theorist Trinh Minh-ha, Haraway is interested in finding "a way to figure 'difference' as a 'critical difference within,' and not as special taxonomic marks grounding difference as apartheid" (Haraway, 1992, 299). Crucially, diffraction attends to the relational nature of difference; it does not figure difference as either a matter of essence or as inconsequential: "a diffraction pattern does not map where differences appear, but rather maps where the *effects* of differences appear" (ibid, 300). Inspired by her suggestion for usefully deploying this rich and fascinating physical phenomenon to think about differences that matter, I elaborate on the notion of diffraction as a tool of analysis for attending to and responding to the effects of difference.[2]

Of course, diffraction is also more than a metaphor. As a physicist, I am taken in by the beauty and depth of this physical phenomenon that I can't help but see nearly everywhere I look in the world. In fact, I will argue that there is a deep sense in which we can understand diffraction patterns—as patterns of difference that make a difference—to be the fundamental constituents that make up the world. But the reader shouldn't expect this ontological point to be evident until the final chapter of the book; there are many lines of argumentation and insights to develop before we can get there, and there is much to learn about the nature of diffraction. I will introduce the notion of diffraction in this chapter but first I want to say something about the different levels on which diffraction operates in the book.

If diffraction is to be a useful tool of analysis it is important to have a thorough understanding of its nature and how it works. It turns out that diffraction is not only an interesting phenomenon in classical physics, a way of making evident some rather remarkable features about the nature of light, including how the effects of differences matter, but diffraction plays an even more fundamental role in quantum physics where it can help us to sort out some crucial epistemological and ontological issues. As I will explain, diffraction is a quantum phenomenon that makes the downfall of classical metaphysics explicit. Diffraction experiments are at the heart of the "wave versus particle" debates about the nature of light and matter. Indeed, the so-called two-slit experiment (which uses a diffraction grating with only two slits) has become emblematic of the mysteries of quantum physics. The Nobel laureate physicist Richard Feynman once said of the two-slit experiment that it is "a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery." Indeed, recent studies of diffraction (interference) phenomena have provided insights about the nature of the entanglement of quantum states, and have enabled physicists to test *meta*physical ideas in the lab. So while it is true that diffraction apparatuses measure the effects of difference, even more profoundly they highlight, exhibit, and make evident the entangled structure of the changing and contingent ontology of the world, including the ontology of knowing. In fact, diffraction not only brings the reality of entanglements to light, it is itself an entangled phenomenon.

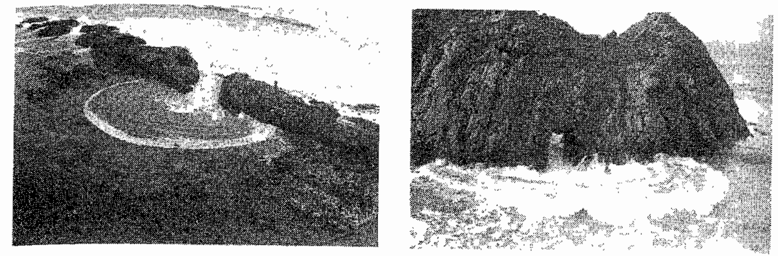
It is impossible to grasp these points and their importance without an in-depth investigation of the physics of diffraction. But getting at the deep meaning of entanglements and the nature of diffraction will require a mode of philosophical inquiry that attends to the details of the physics while also taking seriously insights from philosophy and other fields of study. I will argue that a diffractive mode of analysis can be helpful in this regard if we learn to tune our analytical instruments (that is our diffraction apparatuses) in a way that is sufficiently attentive to the details of the phenomenon we want to understand. So at times diffraction phenomena will be an object of investigation and at other times it will serve as an apparatus of investigation; it cannot serve both purposes simultaneously since they are mutually exclusive; nonetheless, as our understanding of the phenomenon is refined we can enfold these insights into further refinements and tunings of our instruments to sharpen our investigations and so on. But as will perhaps be clear by the end of this chapter, this is precisely an operation of a diffractive methodology on the next level up as it were. The analysis at hand then will require thinking through the details of diffraction as a physical phenomenon, including quantum understandings of diffraction and the important differences they make, in order to tune the diffraction apparatus, in order to explore the phenomenon at hand, which in this case is diffraction, in order to produce a new way of thinking about the nature of difference, and of space, time, matter, causality, and agency, among other important variables.

To summarize, what I am interested in doing is building diffraction apparatuses in order to study the entangled effects differences make. One of the main purposes will be to explore the nature of entanglements and also the nature of this task of exploration. What is entailed in the investigation of entanglements? How can one study them? Is there any way to study them without getting caught up in them? What can one say about them? Are there any limits to what can be said? My purpose is not to make general statements as if there were something universal to be said about all entanglements, nor to encourage analogical extrapolation from my examples to others, nor to reassert the authority of physics. On the contrary, I hope my exploration will make clear that entanglements are highly specific configurations and it is very hard work building apparatuses to study them, in part because they change with each intra-action. In fact it is not so much that they change from one moment to the next or from one place to another, but that space, time, and matter do not exist prior to the intra-actions that reconstitute entanglements. Hence, it is possible for entangled relationalities to make connections between entities that do not appear to be proximate in space and time. (More on this in chapter 7.) The point is that the specificity of entanglements is everything. The apparatuses must be tuned to the particularities of the entanglements at hand. The key question in each case is this: how to responsibly explore entanglements and the differences they make. My hope is that this exploration will provide some insights that will be helpful in the study of other entanglements.

I should perhaps caution the reader as I begin to introduce the notion of diffraction that the full texture, complexity, and richness of this phenomenon will not shine through fully until the entire book has been read—until its diffractive articulation works its way through the grating of the full set of chapters.

Let's begin with an overview of the classical understanding of diffraction. Simply stated, diffraction has to do with the way waves combine when they overlap and the apparent bending and spreading of waves that occurs when waves encounter an obstruction. Diffraction can occur with any kind of wave: for example, water waves, sound waves, and light waves all exhibit diffraction under the right conditions.

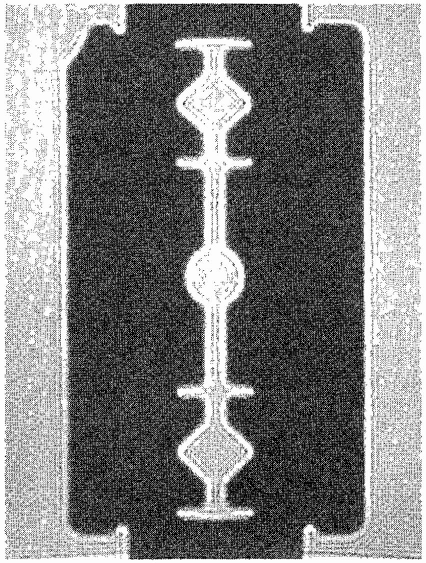
Consider a situation in which ocean waves impinge on a breakwater or some very large barrier with a sizable hole or gap in it. As the waves push through the gap, the waveforms bend and spread out. In particular, the approaching parallel plane waves emerge from the gap in the shape of concentric half circles. The ocean waves are thus diffracted as they pass through the barrier; the barrier serves as a diffraction apparatus for ocean waves (see figure 1).



1 These two photos show the diffraction of ocean waves as they pass through an opening in a barrier. *Photographs by Paul Doherty. Reprinted with permission.*

Similarly, if a person speaks into one end of a cardboard tube, the sound waves spread out in all directions as they emerge from the other end. This is evidenced by the fact that it is possible to hear the sound that emerges without needing to place one's ear directly in line with the cardboard tube, which would be the case if the pressure disturbances in the air emerged from the tube in a narrow stream.

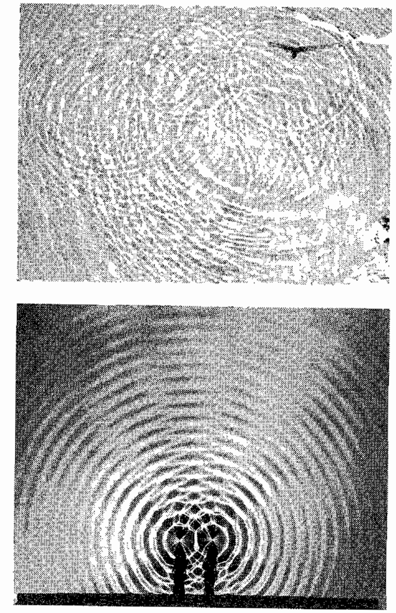
Likewise, light appears to bend when it passes by an edge or through a slit. Under the right conditions, a diffraction pattern—a pattern of alternating light and dark lines—can be observed. Figure 2 shows a diffraction pattern created around the edges of a razor blade.[3] The image you are looking at is the shadow cast by the razor blade when it is illuminated by a monochromatic (single wavelength) point light source.[4] (Diffraction patterns of this kind are ubiquitous but less evident in most everyday encounters because a diffuse light source or one that emits a spectrum of wavelengths, like a light bulb, creates many different overlapping diffraction patterns that disguise one another.) If you look at the image carefully, you'll see that the shadow cast by the razor blade is not the sharply delineated geometrical image one might expect. In particular, there is not a single solid dark area in the shape of the blade surrounded on all sides by a uniformly bright background. Rather, a careful examination reveals an indeterminate outline around each of the edges: along both the inside and outside edges there are alternating lines of dark and light that make the determination of a "real" boundary quite tricky. Perhaps even more surprisingly there are lines of alternating dark and light even into the very center that corresponds to the notched-out part of the blade. Shouldn't that entire area be light? How can there be dark lines in the center at all? How can we understand this pattern that is produced?



2 Photograph of the actual shadow of a razor blade illuminated by a monochromatic light source. Notice the diffraction fringes—the existence of dark lines in light regions and light lines in dark regions created by the diffraction of waves around the inside and outside edges of the blade. *From Francis W. Sears, Mark W. Zemansky, and Hugh D. Young, University Physics, 6th ed. © 1982 by Addison-Wesley Publishing Company, Inc. Reprinted with permission of Pearson Education, Inc.*

It is important to keep in mind that waves are very different kinds of phenomena from particles. Classically speaking, particles are material entities, and each particle occupies a point in space at a given moment of time. Waves, on the other hand, are not things per se; rather, they are disturbances (which cannot be localized to a point) that propagate in a medium (like water) or as oscillating fields (like electromagnetic waves, the most familiar example being light). Unlike particles, waves can overlap at the same point in space. When this happens, their amplitudes combine to form a composite waveform. For example, when two water waves overlap, the resultant wave can be larger or smaller than either component wave. For example, when the crest of one wave overlaps with the crest of another, the resultant waveform is larger than the individual component waves. On the other hand, if the crest of one wave overlaps with the trough of another, the disturbances partly or in some cases completely cancel one another out, resulting in an area of relative calm. Hence the resultant wave is a sum of the effects of each individual component wave; that is, it is a combination of the disturbances created by each wave individually. This way of combining effects is called *superposition*. The notion of superposition is central to understanding what a wave is.[5]

Consider a familiar example. If two stones are dropped into a calm pond simultaneously, the disturbances in the water caused by each stone propagate outward and overlap with each other, producing a pattern that results

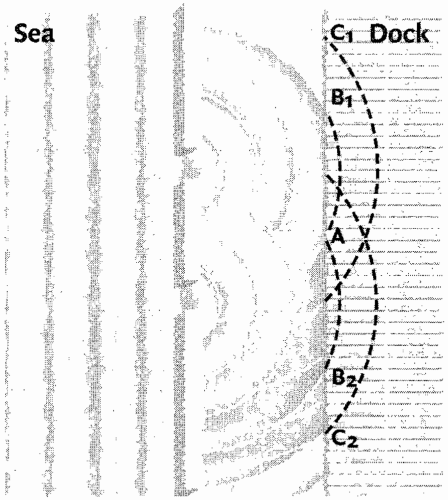


3 Two images of diffraction or interference patterns produced by water waves. The top image (*a*) shows the pattern made by several overlapping disturbances in a pond. The bottom image (*b*) shows a pattern created in a ripple tank made by repeated periodic disturbances at two points. Ripple tanks are a favorite device for demonstrating wave phenomena. This image clearly shows distinct regions of enhancement (constructive interference) and diminishment (destructive interference) caused by the overlapping waves. (The cone shapes that seem to radiate outward are places where the component waves cancel one another out.) *Photograph 3a by Karen Barad. Photograph 3b from Berenice Abbott, "The Science Pictures: Water Pattern," reprinted with permission of Mount Holyoke College Art Museum, South Hadley, Massachusetts.*

from the relative differences (in amplitude and phase) between the overlapping wave components (see figure 3).[6] The waves are said to interfere with each other, and the pattern created is called an interference or diffraction pattern.[7]

A similar pattern can be observed when there are two holes in a breakwater (see figure 4). The circular waveforms that emerge from each of the holes in the barrier combine to form an interference or diffraction pattern. (The resulting pattern looks just like one half of the interference pattern produced by the two stones falling into the pond.)

Walking along the dock, you would feel the boards of the dock moving up and down with the incoming waves. The amount that each board moves up or down depends on the amplitude of the overall wave at each particular point along the dock. If you walked up and down the dock, you would experience the alternating pattern of areas of increasing and decreasing intensities (i.e., height or amplitude) of the overall wave. At point A (the point on the dock directly opposite the midpoint of the breaks in the wall), for example, the intensity of the overall waveform is large, and if you stood on the boards there, you'd feel the large oscillations. If you moved to either side of point A, you would experience a decrease in the amplitude or intensity of the over-

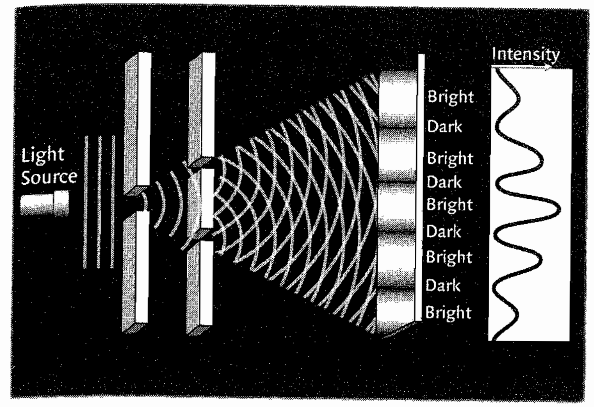


4 A bird's-eye drawing of a breakwater with two similar-sized holes acting as a diffraction grating for incoming water waves. The parallel lines approaching the breakwater and the concentric circles emerging from the breakwater indicate the wave fronts or crests of the waves. A dock positioned to the right measures the amplitude of the incoming waves: as the waves come in toward the dock, they move the individual boards up and down; the amount that each board moves up or down depends on the amplitude of the overall wave at each point along the dock. *Illustration by Nicolle Rager Fuller for the author.*

all waveform. At points such as B_1 and B_2, where the crests of the waves spreading out from one of the breaks in the wall are meeting the troughs from the other, there would be relative calm, and you wouldn't feel the boards move much at all. But farther down the dock at points such as C_1 and C_2 where the crests of the waves spreading out from the two breaks in the wall meet up with one another, and similarly for the troughs, the overall wave amplitude picks up again, and the boards at those locations would oscillate up and down a fair amount (though not as much as at point A). This alternating pattern of wave intensity is characteristic of interference or diffraction patterns.[8]

Figure 5 shows the analogous situation for light waves. Two slits are cut into a screen or some other barrier that blocks light. A target screen is placed behind and parallel to the barrier screen that has the slits in it. When the slits are illuminated by a light source, a diffraction or interference pattern appears on the target screen. That is, there is a pattern marked by alternating bands of bright and dark areas: bright spots appear in places where the waves enhance one another—that is, where there is "constructive interference"—and dark spots appear where the waves cancel one another—that is, where there is "destructive interference."

Now we are in a position to understand the diffraction pattern created by a razor blade as in figure 2. Physicists understand diffraction as the result of



5 A drawing of a side view of a two-slit experiment using a coherent monochromatic light source. The screen exhibits a characteristic diffraction or interference pattern with alternating bands of bright (i.e., places where the light waves are in phase and constructively interfere with one another) and dark (i.e., places where the light waves are out of phase and destructively interfere with one another) areas. The graph to the right shows how the intensity of the light varies with the distance along the screen. *Illustration by Nicolle Rager Fuller for the author.*

the superposition or interference of waves.[9] In the case of the razor blade, then, the diffraction pattern can be understood to result from the combining (i.e., superposition) of individual wave components as they emerge past the various edges of the razor. For example, consider the bright spot that appears at the place on the screen that corresponds to the very center of the circular part of the gap in the blade (the middle of the picture). How can we understand the existence of this bright spot, or even more surprisingly the existence of dark lines in the gap? Where does the alternation of light and dark lines come from? The diffraction pattern in the gap is created by the superposition of light waves coming from the edges of the razor. Where they meet in phase, a bright spot appears. The dark spots are places where the waves are out of phase with one another, that is, where they cancel one another out. The pattern that appears has to do with the precise geometry of the razor blade, in particular, in this case, its symmetries.[10]

It may be a bit challenging to think through the rather complex geometry of a razor blade; thinking about a simpler case may be helpful. Consider what happens when a light source illuminates a small opaque object like a BB (a small sphere made of lead). One might expect a round shadow to be cast on the wall behind the BB. But on closer examination, it becomes evident that there is a bright spot at the center of the shadow.[11] How is this possible? The answer is it's part of the diffraction pattern that results from the superposition of component waves as they emerge on the other side of the BB. Just as in figure 4, where the waves combine to form a wave with a large amplitude at point A (opposite the center point between the gaps in the breakwater) as a result of the waves arriving in phase, the waves that pass by the edges of the BB meet in phase with one another at the center of the shadow. Surfers know this phenomenon well, since they are sometimes able to catch really nice waves on the other side of a large boulder sitting offshore. That is, they can take advantage of the diffraction patterns created by rocks or pieces of land that stick out near the shore. These surfers are literally riding the diffraction pattern.

There are many other opportunities in daily life to observe diffraction or interference phenomena. For example, the rainbow effect commonly observed on the surface of a compact disc is a diffraction phenomenon. The concentric rings of grooves that contain the digital information act as a diffraction grating spreading the white light (sunlight) into a spectrum of colors.[12] The swirl of colors on a soap bubble or a thin film of oil on a puddle is also an example of a diffraction or interference phenomenon.[13] The iridescence of peacock feathers, or the wings of certain dragonflies, moths, and butterflies—the way the hue of these colors changes with the changing viewing position of the observer—is also a diffraction effect. From the perspective of classical physics, diffraction patterns are simply the result of differences in (the relative phase and amplitudes of) overlapping waves.

Some physicists insist on maintaining the historical distinction between interference and diffraction phenomena: they reserve the term "diffraction" for the apparent bending or spreading of waves upon encountering an obstacle and use "interference" to refer to what happens when waves overlap. However, the physics behind diffraction and interference phenomena is the same: *both result from the superposition of waves*. As the physicist Richard Feynman points out in his famous lecture notes (1964), the distinction between interference and diffraction is purely a historical artifact with no physical significance. And as the authors of a popular physics text point out: "Diffraction is sometimes described as 'the bending of light around an obstacle.' But the process that causes diffraction is present in the propagation of *every* wave. When part of the wave is cut off by some obstacle, we observe diffraction effects that result from interference of the remaining parts of the wave fronts. . . . Thus diffraction plays a role in nearly all optical phenomena" (Young and Freedman 2004, 1369). I use the terms "diffraction" and "interference" interchangeably without granting significance to the historical contingencies by which they have been assigned different names.

In summary, diffraction patterns are a characteristic behavior exhibited by waves under the right conditions. Crucially, diffraction patterns mark an important difference between waves and particles: according to classical physics, *only waves produce diffraction patterns; particles do not* (since they cannot occupy the same place at the same time). Indeed, a diffraction grating is simply an apparatus or material configuration that gives rises to a superposition of waves. In contrast to reflecting apparatuses, like mirrors, which produce images—more or less faithful—of objects placed a distance from the mirror, diffraction gratings are instruments that produce patterns that mark differences in the relative characters (i.e., amplitude and phase) of individual waves as they combine.

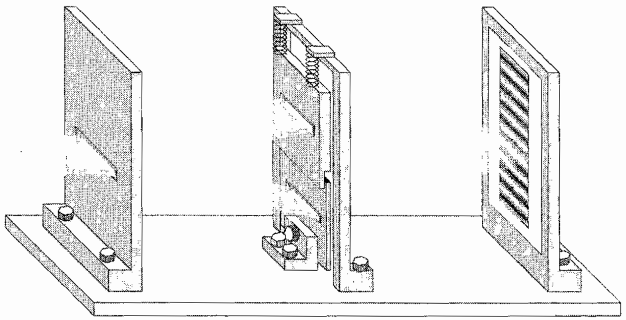
So unlike the phenomenon of reflection, which can be explained without taking account of the wavelike behavior of light (i.e., it can be explained using an approximation scheme called "geometrical optics" whereby light might well be a particle that bounces off surfaces), diffraction makes light's wavelike behavior explicit (i.e., it can only be accounted for by using the full theory of "physical optics").

Following this overview of a classical understanding of diffraction phenomena, it would seem an apt moment to proceed with a discussion of a quantum understanding of diffraction. In a sense, it takes the remainder of this book to do this. It is important to go slowly and carefully. At this juncture, we must be content with some hints of what is to come.

It is perhaps not too soon to introduce the diagram of an experiment that will take on a great deal of significance throughout this book (see figure 6). This diagram, based on drawings by the physicist Niels Bohr, is emblematic of the kinds of experiments that proved to be of profound historical significance in the development of quantum theory and, even more crucially, have been and continue to be foundational to understanding the deep and far-reaching insights of this highly counterintuitive theory.

Figure 6 shows a modified two-slit diffraction or interference experiment. The middle partition with the two slits serves as the two-slit diffraction grating, while the screen on the right displays the diffraction pattern (alternating bands of intensity). (The first partition with a single slit is there for technical reasons.)[14] The significance of the modification—the fact that the top slit is attached to the support by two springs—will be explained later.

Now, one of the most remarkable empirical findings, which in fact con-



6 Illustration of the famous two-slit diffraction or interference experiment, based on original diagrams sketched by Niels Bohr. In this modified two-slit experiment, the top slit is attached by springs to the support. The bottom slit is attached to the frame. The significance of this modification will be explained later. (The existence of the first barrier with a single slit simply indicates that a coherent light source is being used.) From P. Bertet et al., "A Complementarity Experiment with an Interferometer at the Quantum-Classical Boundary," *Nature* 411 (2001): 167, figure 1. Reprinted with permission of Macmillan Publishers Ltd.

stituted a key piece of evidence leading to the development of quantum physics, is that under certain circumstances *matter* (generally thought of as being made of particles) is found to produce a diffraction pattern! That is, we find bands or areas where significant numbers of particles hit the screen alternating with areas where hardly any particles hit the screen. But this is not at all how we would expect particles to behave: we would expect the bulk of the particles to wind up opposite one slit or the other (i.e., no alternating band pattern). And yet diffraction effects have been observed for electrons, neutrons, atoms, and other forms of matter. And even more astonishing, this diffraction pattern is produced even if the particles go through the diffraction grating one at a time (that is, even if there is, if you will, nothing else around for each particle to interfere with, whatever that might mean).

Much to their surprise, Clinton Davisson and Lester Germer serendipitously confirmed this result for electrons in 1927. They were firing slow-moving electrons at a crystalline nickel target when they had an accidental break in the vacuum. After fixing the vacuum, they reheated the nickel sample to repair damage to the target and began their experiment once again. This time, they saw a remarkable pattern in their results: the electrons that were collected formed a diffraction pattern. They had accidentally discovered direct evidence for the wave behavior of matter. What had happened

was that when they reheated the crystal target, the nickel fused into larger crystal, forming a perfect diffraction grating for the electrons.[15]

The Davisson-Germer experiment showed that under some circumstances, matter (in this case electrons) exhibits wavelike behavior. Since the Davisson and Germer experiment, many other experiments have confirmed this result for other kinds of matter as well. That is, there is direct empirical evidence that *matter*—not just light—manifests *wave* behavior under the right experimental circumstances. But this seems to fly in the face of other equally convincing evidence that electrons sometimes behave like particles. Significantly, the converse is true as well: separate experiments have confirmed the equally counterintuitive result that *light* manifests *particle* behavior under certain circumstances (and wave behavior under other circumstances).

As we have seen, *diffraction patterns are evidence of superpositions*. But how can we understand this result, then? It makes sense to talk about the superposition of waves, but not particles. This result is paradoxical. Physicists call it the "wave-particle duality paradox" of quantum theory, and the modified two-slit experiment plays a key role in sorting out the epistemological and ontological issues involved.[16] Indeed, as I will discuss in detail, understanding the counterintuitive results of experiments such as the one sketched in figure 6 involves *a crucial rethinking of much of Western epistemology and ontology*. Significantly, these experiments illuminate the very nature of superpositions and their relationship to the so-called entanglement of states, which physicists now believe lies at the heart of all quantum phenomena and a great deal of "quantum weirdness." There is much to say about these issues. I have detailed discussions of them in later chapters. For now, I would like the reader to merely hold on to the suggestion of the complexity and profundity of diffraction phenomena and to keep this in mind whenever this notion is invoked, either figuratively, methodologically, or in reference to a physical phenomenon.

It has now become routine to use diffraction experiments to determine different features of matter. Generally this works in one of two complementary ways: sometimes the goal of a diffraction experiment is to learn about the nature of the substance that is being passed through a diffraction grating, and sometimes it's to learn about the diffraction grating itself. Let's consider one example of each situation. The Davisson-Germer experiment is an example of the first technique: a crystal is used as a diffraction grating, and a beam of electrons is passed through the crystal grating. This experiment tells us something important about the nature of electrons: namely, that under certain circumstances they exhibit wave behavior. The second situation applies when a scientist uses x-ray diffraction techniques to discern the structure of a substance: in this case, the substance being investigated is the diffraction grating itself. For example, the way x-ray diffraction generally works is that x-rays (of a known wavelength) are fired at the sample (i.e., the crystal or other substance that serves as the diffraction grating). Since the wavelength of the x-rays is known in advance, it is possible to "work backward" from the diffraction pattern to deduce features of the diffraction grating (such as the distance between "slits," in this case the molecules or atoms) and in this way determine the structure of the substance in question. This technique was used by Rosalind Franklin to determine the structure of DNA. Hence we can use diffraction experiments to learn either about the object being passed through the diffraction grating or about the grating itself.[17]

Physicists have noted an interesting analogy between the fields of mechanics and optics. This analogy entails a mathematical correspondence between optical and mechanical variables. Physicists have invoked this analogy to help them gain insights about both mechanics and optics. I want to point out the nature of the parallel and use this opportunity both to explain a few important points about optics and also to say something about the important question of the relationship between classical or Newtonian physics and quantum physics.[18]

Some preliminary background in optics may be helpful. There is an important general point to be made about the ways in which physicists study optics. First of all, the study of optics is divided into two categories: classical optics (optics studied from the point of view of classical physics), on the one hand, and quantum optics (where quantum mechanics is used to understand phenomena involving light and its interactions with matter), on the other. There are also two primary modes of the investigation of classical optics: *geometrical optics* and *physical optics*. Whereas reflection can be explained using geometrical optics, diffraction cannot be understood using this technique. To understand diffraction, physicists use physical optics.

Geometrical optics is essentially an approximation tool for studying different optical instruments (e.g., different configurations of lenses, mirrors, prisms, optical fibers, etc.). Geometrical optics is focused primarily on where light goes or what it can be made to do when it impinges on or passes into or through any number of different optical instruments. The approximation that is used is to simply treat light as a "ray" (which is simply an indicator of the direction of propagation of the light, devoid of any ontological commitment about the nature of light). That is, in the study of geometrical optics, the nature of light is considered to be of no consequence. In particular, geometrical optics does not provide any method for distinguishing between wave and particle behaviors; the whole question of the nature of light is bracketed.[19] By contrast, the field of physical optics is interested in, and has at its disposal, techniques for investigating the nature of light itself. That is, light is not merely a tool but an object of inquiry as well. The two-slit diffraction or interference experiment has been indispensable in efforts to discern the nature of light (and of nature).

The ray approximation of geometrical optics works well when the wavelength of light is small compared with the physical dimensions of the objects it is interacting with, such as the size of a slit that the light passes through. If the wavelength is small compared with the slit size, then diffraction effects such as the bending of light will be too small to be noticeable. However, when the wavelength is approximately the same size as the slit or larger, then diffraction effects (i.e., the wave nature of light) cannot be ignored. Hence when the wavelength of light is approximately the same size as, or larger than, the object it encounters (e.g., sizable in comparison to the width of the slits), the techniques of physical optics—the full mathematical machinery that is attentive to the wave nature of light—must be used to correctly account for the phenomenon. In effect, then, geometrical optics is merely a shortcut way of deriving the correct results when the wavelength happens to be small enough compared to other relevant dimensions in the experiment.

Let's return to the analogy between optics and mechanics. The analogy is between geometrical optics and classical Newtonian mechanics, on the one hand, and physical optics and quantum mechanics on the other. The crux of the analogy is this: when in the case of a particular experiment the wave nature of light or matter is not significant (i.e., when the wavelength is small relative to other important dimensions), it may be possible to use classical mechanics (geometrical optics) as a shortcut to the more rigorous analysis that quantum mechanics (physical optics) provides.[20] So whereas classical mechanics and geometrical optics are (nowadays understood to be) approximation schemes that are useful under some circumstances, quantum mechanics and physical optics are understood to be formalisms that represent the full theory and can account for phenomena at all length scales. Significantly, quantum mechanics is not a theory that applies only to small objects; rather, quantum mechanics is thought to be the correct theory of nature that applies at all scales. As far as we know, the universe is not broken up into two separate domains (i.e., the microscopic and the macroscopic) identified with different length scales with different sets of physical laws for each.

I now turn my attention to questions of methodology. The use of optical metaphors in discussing matters of epistemology and methodology is prodigious. Keller and Grontkowski (1983) trace the intertwining of vision and knowledge in Western thought and argue that "the tradition of grounding our epistemological premises in visual analogies dates back to the Greeks" (208). It is hardly surprising, then, that discussions of methodology would reflect this practice. Indeed, representationalism—the belief that words, concepts, ideas, and the like accurately reflect or mirror the things to which they refer—makes a finely polished surface of this whole affair. And it has encouraged the belief that it is possible to turn the mirror back on oneself, as it were, thus spawning various candidates for "reflexive" methodologies.[21]

Mirrors reflect. To mirror something is to provide an accurate image or representation that faithfully copies that which is being mirrored. Hence mirrors are an often-used metaphor for representationalism and related questions of reflexivity. For example, a scientific realist believes that scientific knowledge accurately reflects physical reality, whereas a strong social constructivist would argue that knowledge is more accurately understood as a reflection of culture, rather than nature.

Reflexivity is a proposed critical scholarly practice that aims to reflect on, and systematically take account of, the investigator's role as an instrument in the constitution of evidence. Reflexivity aims to acknowledge the tripartite arrangement between objects, representations, and knowers that produces knowledge, as opposed to less-reflexive modes of investigation that leave the knower out of the equation, focusing attention narrowly on the relationship between objects and their representations. Various empirical fields of study have given considerable attention to reflexive methodologies. In science studies, for example, there has been significant discussion about reflexivity. Some scholars paid it homage, some adopted it as a basic tenet but failed to enact their stated commitments, others argued vigorously against its alleged virtues, and other groups claimed to have moved beyond the terms of the debate altogether.[22] For example, some science studies scholars used the methods of reflexivity to critique the social realism of some of the field's own practitioners. In particular, reflexive criticism brought with it an acknowledgment that some of the same social scientists who were being vigilant in questioning the avowed *scientific realism* of their objects of study—namely, laboratory scientists—unreflectively engaged in *social realism*, namely, in the reification of important categories of the "social" and the privileging of them as explanatory factors over the "natural." While acknowledging this important critique of SSK (sociology of scientific knowledge) approaches (especially the "strong programme" in the sociology of scientific knowledge), other science studies scholars were less interested in the debates about reflexivity because they had already developed and adopted other approaches (e.g., actor-network theory, feminist science studies approaches) that seek to take account of the role of natural as well as social factors in scientific practices.

Notably, feminist science studies scholars have offered poignant critiques of relativism and reflexivity from early on. (Undoubtedly, the fact that many feminist science studies scholars are scientists has played a significant role in its sustained and unflinching commitment to take nature, objectivity, and the efficacy of science seriously. There is also an important sense in which these commitments are clearly feminist.) In particular, feminist science studies scholars have argued that reflexivity has proved insufficient on at least two important grounds.[23] First of all, for the most part, mainstream science studies (in all its various incarnations) has ignored crucial social factors such as gender, race, class, sexuality, ethnicity, religion, and nationality. The irony is that while these scholars insist on the importance of tracking "science-in-the-making" by attending to specific laboratory practices, for the most part they continue to treat social variables such as gender as preformed categories of the social. That is, they fail to attend to "gender-in-the-making"—the production of gender and other social variables as constituted through technoscientific practices.[24] Thus, despite the fact that feminist science studies scholars have been arguing from the beginning for an understanding of gender-and-science-in-the-making, mainstream science studies accounts have neglected this crucial point. Significantly, to the degree that they fail to appreciate this fact, they underestimate the mutual constitution of the "social" and the "scientific," thus undermining their own project. Relatedly, mainstream science studies scholars seem to be unaware of the fact that the nature-culture dichotomy has been challenged vigorously on multiple grounds by feminist, poststructuralist, postcolonialist, queer, and other critical social theorists, and that attending to the issues they raise is an integral part of questioning the constitution of the nature-culture dichotomy and the work it does: not only *that* it matters, but *how* it matters and *for whom*.

A second significant difficulty is the fact that reflexivity is founded on representationalism. Reflexivity takes for granted the idea that representations reflect (social or natural) reality. That is, reflexivity is based on the belief that practices of representing have no effect on the objects of investigation and that we have a kind of access to representations that we don't have to the objects themselves. Reflexivity, like reflection, still holds the world at a distance. It cannot provide a way across the social constructivist's allegedly unbridgeable epistemological gap between knower and known, for reflexivity is nothing more than iterative mimesis: even in its attempts to put the investigative subject back into the picture, reflexivity does nothing more than mirror mirroring. Representation raised to the nth power does not disrupt the geometry that holds object and subject at a distance as the very condition for knowledge's possibility. Mirrors upon mirrors, reflexivity entails the same old geometrical optics of reflections.

By contrast, diffraction is not reflection raised to some higher power.[25] It is not a self-referential glance back at oneself. While reflection has been used as a methodological tool by scholars relying on representationalism, there are good reasons to think that diffraction may serve as a productive model for thinking about nonrepresentationalist methodological approaches.

I turn my attention next to exploring some important aspects of diffraction that make it a particularly effective tool for thinking about socialnatural practices in a peformative rather than representationalist mode. But first I want to raise an important cautionary point. In the introduction, I emphasized that my method will *not* entail analogical argumentation. I have every intention of following through on this promise. In this regard, it is important not to confuse the fact that I am drawing on an optical phenomenon for my inspiration in developing certain aspects of my methodological approach (which, as I pointed out earlier, has its place in a long and honored tradition of using visual metaphors as a thinking tool) with the nature of the method itself. In particular, calling a method "diffractive" in analogy with the physical phenomenon of diffraction does *not* imply that the method itself is analogical.[26] On the contrary, my aim is to disrupt the widespread reliance on an existing optical metaphor—namely, reflection—that is set up to look for homologies and analogies between separate entities. By contrast, diffraction, as I argue, does not concern homologies but attends to specific material entanglements.

The table summarizes some of the main differences entailed in shifting our thinking from questions of reflection to those of diffraction. At this juncture, some of the items in the table may not be clear and will not be clarified until much more is explained about diffraction as a physical phenomenon (indeed, until it is understood as a material-discursive phenomenon that makes the effects of different differences evident). But hopefully even at this point it will serve as a useful heuristic to mark the kinds of shifts that are at issue in moving away from the familiar habits and seductions of representationalism (reflecting on the world from outside) to a way of understanding the world from within and as part of it, as a diffractive methodology requires.

Diffraction	*Reflection*
diffraction pattern marking differences from within and as part of an entangled state	mirror image reflection of objects held at a distance
differences, relationalities objectivity is about taking account of marks on bodies, that is, the differences materialized, the differences that matter	sameness, mimesis objectivity is about reflections, copies that are homologous to originals, authentic, free of distortion
diffractive methodology	reflexivity
performativity subject and object do not preexist as such, but emerge through intra-actions	representationalism preexisting determinate boundary between subject and object
entangled ontology material-discursive phenomena	separate entities words and things
onto-epistem-ology knowing is a material practice of engagement as part of the world in its differential becoming	ontology | epistemology binary knowledge is true beliefs concerning reflections from a distance knower | known binary seeing/observing/knowing from afar
intra-acting within and as part of	interacting of separate entities
differences emerge within phenomena agential separability real material differences but without absolute separation	inside/outside absolute separation no difference interior/exterior
diffraction/difference pattern intra-acting entangled states of nature cultures	words mirror things social | natural binary nature | culture binary
about making a difference in the world about taking responsibility for the fact that our practices matter; the world is materialized differently through different practices (contingent ontology)	about representations about finding accurate representations about the gaze from afar

phenomena are objective referents accountability to marks on bodies accountability and responsibility taking account of differences that matter	things are objective referents accountability entails finding an authentic mirror representation of separate things
ethico-onto-epistem-ology ethics, ontology, epistemology not separable	ethics | ontology | epistemology separate fields of study
reading through (the diffraction grating) transdisciplinary engagement attend to the fact that boundary production between disciplines is itself a material-discursive practice; how do these practices matter?	reading against (some fixed target/mirror) privilege one discipline read other(s) against it
subject, object contingent, not fixed	subject | object fixed
respectful engagement that attends to detailed patterns of thinking of each; fine-grained details matter	reify, simplify, make the other into a separate object less attentive to and able to resolve important details, dynamics, how boundaries are made
Summary accounting for how practices matter	reflecting on representations

First and foremost, as Haraway suggests, a diffractive methodology is a critical practice for making a difference in the world. It is a commitment to understanding which differences matter, how they matter, and for whom. It is a critical practice of engagement, not a distance-learning practice of reflecting from afar. The agential realist approach that I offer eschews representationalism and advances a performative understanding of technoscientific and other naturalcultural practices, including different kinds of knowledge-making practices. According to agential realism, knowing, thinking, measuring, theorizing, and observing are material practices of intra-acting within and as part of the world. What do we learn by engaging in such practices? We do not uncover preexisting facts about independently

existing things as they exist frozen in time like little statues positioned in the world. Rather, we learn about phenomena—about specific material configurations of the world's becoming. The point is not simply to put the observer or knower back in the world (as if the world were a container and we needed merely to acknowledge our situatedness in it) but to understand and take account of the fact that we too are part of the world's differential becoming. And furthermore, the point is not merely that knowledge practices have material consequences but that *practices of knowing are specific material engagements that participate in (re)configuring the world*. Which practices we enact matter—in both senses of the word. Making knowledge is not simply about making facts but about making worlds, or rather, it is about making specific worldly configurations—not in the sense of making them up ex nihilo, or out of language, beliefs, or ideas, but in the sense of materially engaging as part of the world in giving it specific material form. And yet the fact that we make knowledge not from outside but as part of the world does not mean that knowledge is necessarily subjective (a notion that already presumes the preexisting distinction between object and subject that feeds representationalist thinking). At the same time, objectivity cannot be about producing undistorted representations from afar; rather, objectivity is about being accountable to the specific materializations of which we are a part. And this requires a methodology that is attentive to, and responsive/responsible to, the specificity of material entanglements in their agential becoming. The physical phenomenon of diffraction makes manifest the extraordinary liveliness of the world.[27]

Crucially, diffraction effects are attentive to fine detail. For example, consider the importance of the detailed bands of dark and light in the diffraction pattern made by a razor blade (figure 2). Also consider the fact that the details of diffraction patterns depend on the details of the apparatus: for example, it depends on the number of slits (it matters if there are three slits instead of two; some diffraction gratings have thousands of tiny parallel "lines"—narrow slits—per inch), the spacing between slits, the size of the slits, and the wavelength of the light source. If any of these parameters is changed, the pattern can be significantly different. Furthermore, diffraction gratings can be used to exhibit some of the smallest details of nature (at least the smallest levels that we have successfully explored). For example, diffraction gratings can be used to measure the spectrum of light that is characteristic of each kind of atom. Each atom in the periodic table has a characteristic set of energy states (different "orbits" that the electron can be in), and when an electron "jumps" from a higher energy level to a lower one, it emits light of a corresponding wavelength (e.g., the visible spectrum of hydrogen has a red line, a blue line, and two violet lines). Therefore the light spectrum of an atom indicates its possible energy levels. The differences in energy levels are tiny (we're talking about changes inside an atom). And yet, upon closer examination, we can see even-finer details. It turns out that it is possible to resolve atomic spectra into something called "fine structure" and even "hyperfine structure" (in which case a single line of color can further be resolved into two or more lines of color, indicating very fine differences indeed). Even beyond this, in 1947 Willis Lamb and Robert Retheford were able to detect an extremely tiny shift in the hydrogen spectrum that is due to a feature of the theory of quantum electrodynamics (i.e., the quantum theory of electromagnetism) that seems more like a fairy tale physicists tell themselves than something that is measurable. According to quantum electrodynamics, the "vacuum" (which, classically speaking, refers to the void) is a state in which everything that can possibly exist exists in some potential form. The lively potentiality of the vacuum creates "vacuum fluctuations," which produce the Lamb shift in the hydrogen spectrum. That Lamb and Retheford were able to measure this tiny shift is remarkable; that there is a possibility of measuring the effects of unrealized possibilities is nothing short of astonishing. Indeed, the Lamb shift constitutes one of the most accurate tests we have of the theory of quantum electrodynamics.[28] We in fact have empirical confirmation of this seething potentiality! Small details can make profound differences.

Attention to fine details is a crucial element of this methodology. The diffractive methodology that I use in thinking insights from scientific and social theories through one another differs from some of the more usual approaches in a significant fashion. I am not interested in reading, say, physics and poststructuralist theory against each other, positioning one in a static geometrical relation to the other, or setting one up as the other's unmovable and unyielding foil. Nor am I interested in bidirectional approaches that add the results of what happens when each takes a turn at playing the foil, as it were. So unlike the all-too-common approaches that are anxious to explore unilaterally the lessons of physics for social and political theories, exploiting what is seen as the greater epistemological value of the natural sciences over the human sciences, or to take a contrary instance, attempts by scholars who would counter the overblown authority of science by suggesting a reversal whereby the social sciences would be a model for the natural sciences, my approach is to place the understandings that are generated from different (inter)disciplinary practices in conversation with one another.[29] That is, my method is to engage aspects of each in *dynamic* relationality to the other, being attentive to the iterative production of boundaries, the material-discursive nature of boundary-drawing practices, the constitutive exclusions that are enacted, and questions of accountability and responsibility for the reconfigurings of which we are a part. That is, the diffractive methodology that I use in thinking insights from different disciplines (and interdisciplinary approaches) through one another is attentive to the relational ontology that is at the core of agential realism. It does not take the boundaries of any of the objects or subjects of these studies for granted but rather investigates the material-discursive boundary-making practices that produce "objects" and "subjects" and other differences out of, and in terms of, a changing relationality. If, unlike multidisciplinary or interdisciplinary approaches, a transdisciplinary approach "does not merely draw from an array of disciplines but rather inquires into the histories of the organization of knowledges and their function in the formation of subjectivities . . . mak[ing] visible and put[ting] into crisis the structural links between the disciplining of knowledge and larger social arrangements" (Hennessy 1993, 12), then the latter approach contains some of the needed elements.[30] Importantly, it is crucial that in using a diffractive methodology one is attentive to fine details of different disciplinary approaches. What is needed are respectful engagements with different disciplinary practices, not coarsegrained portrayals that make caricatures of another discipline from some position outside it. My aim in developing a diffractive methodology is to attempt to remain rigorously attentive to important details of specialized arguments within a given field without uncritically endorsing or unconditionally prioritizing one (inter)disciplinary approach over another.[31]

Hence the diffractive methodology that I propose enables a critical rethinking of science and the social in their relationality. What often appears as separate entities (and separate sets of concerns) with sharp edges does not actually entail a relation of absolute exteriority at all. Like the diffraction patterns illuminating the indefinite nature of boundaries—displaying shadows in "light" regions and bright spots in "dark" regions—the relation of the social and the scientific is a relation of "exteriority within" (see, for example, figure 2).

As such, the diffractive methodology that I propose stands in stark contrast to some of the more usual modes of scholarly engagement that aim to "bridge" the humanities and natural sciences. Importantly, a diffractive approach has no patience for tricks with mirrors, where, for example, the macroscopic is said to mirror the microscopic, or the social world is treated as a reflection of the metaphysics of individualism perfected in atomic theory, and so on. The drawing of analogies, like that between special relativity and the cubist school of painting, for instance, or the "influence model" mode of investigation, where specific causal linkages are suggested for the analogies, as in the gathering of historical evidence on behalf of the hypothesis that the cubists were directly influenced by Einstein, for example, can be very interesting. But these common modes of analysis are only of limited value, and insufficient for understanding the deeper philosophical issues at stake in learning how to "diffract the rays of technoscience [and other social practices] so that we get more promising interference patterns on the recording films of our lives and bodies" (Haraway 1997, 16). This diffractive methodology enables me to examine in detail important philosophical issues such as the conditions for the possibility of objectivity, the nature of measurement, the nature of nature and meaning making, the conditions for intelligibility, the nature of causality and identity, and the relationship between discursive practices and the material world.

Significantly, as I have already mentioned, my diffractive methodology maintains a standard of rigor that enables me to return to my starting point and address anew unsettled questions in the foundations of quantum physics. In particular, I argue that agential realism can in fact be understood as a legitimate interpretation of quantum mechanics, addressing crucial issues that Bohr's framework of complementarity does not satisfactorily resolve. Likewise, using several different case studies, I demonstrate the usefulness of an agential realist approach for negotiating difficulties in some of the other fields that I draw on, such as feminist theory, poststructuralist theory, and science studies. Furthermore, I show that agential realism provides interesting insights concerning the nature of these entangled considerations: what is at issue is not mere homologies between different subject matters of different disciplines, but rather the specific material linkages and how these intra-relations matter. Although the kinds of difficulties that plague these diverse fields no doubt engage substantively disparate issues, they are not altogether disconnected, analytically, epistemologically, or ontologically. In fact, according to agential realism, the analysis of entangled practices requires a nonadditive approach that is attentive to the intra-action of multiple apparatuses of bodily production. Finally, in the chapters that follow, I offer a detailed discussion of quantum physics and the nature of the phenomenon of diffraction, pushing our understanding well beyond the classical physics view, in a way that promises a significant deepening of how we might understand diffraction both as a material-discursive practice and as a critical practice.

PART II INTRA-ACTIONS MATTER

THREE

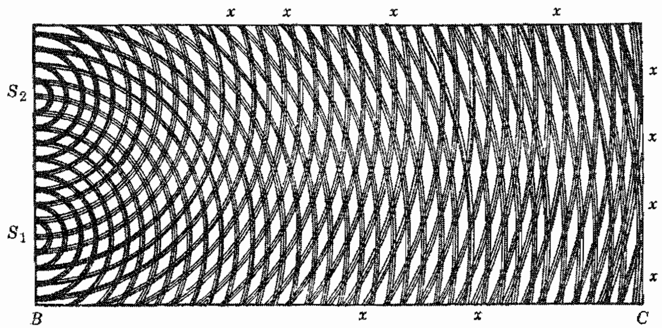
Niels Bohr's Philosophy-Physics: Quantum Physics and the Nature of Knowledge and Reality

Representationalism and Newtonian physics have roots in the seventeenth century. The assumption that language is a transparent medium that transmits a homologous picture of reality to the knowing mind finds its parallel in a scientific theory that takes observation to be the benign facilitator of discovery, a transparent lens passively gazing at the world. Just as words provide descriptions or representations of a preexisting reality, observations reveal preexisting properties of an observation-independent reality. In the twentieth century, both the representational or mimetic status of language and the inconsequentiality of the observational process have been called into question.

Niels Bohr argued with brilliance, passion, and persistence that quantum physics not only revolutionized physics but shook the very foundation of Western epistemology. Indeed, Bohr's philosophy-physics (the two were inseparable for him) poses a radical challenge not only to Newtonian physics but also to Cartesian epistemology and its representationalist triadic structure of words, knowers, and things.

ON THE NATURE OF LIGHT AND MATTER

Nothing less than the true ontological nature of light was at stake. Some authorities argued that light is a wave; others argued that it is a particle. Thomas Young's two-slit experiment was a singular defining moment in the centuries-long debate concerning the nature of light.[1] Newton's "corpuscular" theory of light still held sway in the early nineteenth century. But the power of all authority—even Sir Isaac's—wanes in the face of contrary empirical evidence, and Young's experiment delivered the final blow to the corpuscular or particle theory, providing incontrovertible evidence that light is a wave. The presence of characteristic alternating bands of dark and light—a pattern readily accounted for using the principle of interference and surely inexplicable by any means that would entertain the thought of light being a particle—was the final adjudicator in the long-standing debate (see figure 7).



7 Thomas Young's original drawing showing interference effects in overlapping waves (from Thomas Young, *Philosophical Transactions*, 1803). Notice that if you place your eye near the left edge and sight at a gazing angle along the figure, you can clearly see the alternating bright and dark regions emanating outward from the sources, indicating areas of constructive and destructive interference respectively (as noted in Haliday and Resnick 1986, 995). *Original drawing by Thomas Young, published in* Philosophical Transactions *(1803). Photo from David Haliday and Robert Resnick,* Physics, Part Two, *3rd ed., extended version (New York: Wiley, 1986), 995. Reprinted with permission of Robert Resnick.*

Or so it is explained in the Whiggish historical accounts that fill physics textbooks. Although this is the stuff of a good pedagogical tale, it is historically inaccurate. As Jed Buchwald, a historian of science, contends in *The Rise of the Wave Theory of Light: Optical Theory and Experiment in the Early Nineteenth Century*, "The replacement of the [particle] theory by the wave theory was . . . more a function of a change in the canons of what a theory must do than of its failing abysmally to explain some new experiment" (1989, xiii). Buchwald argues that between the advent of Young's presentation of his law of interference and the acceptance of his ideas a decade or so later, there was a sea change in experimental practice, which included significant changes in the mathematical apparatus facilitating more consistent comparison between experimental results and theory (from geometrical to algebraic methods); the reporting apparatus (from a lack of standards to accepted standards that required analysis, tabulation of results, and comparisons based on more than a small range of what the formulas predicted); and the technical apparatus (from a lack of attention to accuracy to standards for eliminating and computing errors). There was also an important sea change in the conceptual apparatus (from rays to waves), making possible a shift from geometrical models to the more rigorous requirements of a theory of physi-

cal optics. Indeed, the historical evidence shows that Young strategically distanced himself from any explicit advocacy of a wave theory of light. Being sensitive to the authority that Newton still held over the scientific community in the century following the publication of *Opticks*, Young remained purposefully agnostic on the nature of light (working with the notion of a "ray" of light) and presented his law of interference as an empirical law before the Royal Society on July 1, 1802. In fact, the two-slit experiment is not even mentioned in the paper but rather is described in his *Lectures* of 1807. Indeed, there is some doubt as to whether Young actually ever succeeded in achieving the celebrated interference pattern for the two-slit experiment that bears his name. Some historians of science claim that Young either never performed the two-slit experiment (Worrall 1976) or used slits that were too far apart and actually concentrated his observations on diffraction fringes from a single slit rather than the interference fringes produced by the effect of both slits (Kipnis 1991). Historians of science disagree about the cause of the immediate negative reception that Young's ideas on interference received. In any case, his account was not accepted before 1816 (Kipnis 1991, 86–89, 119, 138–64), and the heated debate of particles versus waves continued through the mid-1830s (Buchwald 1989, xiii).

Not the result of one singularly defining experiment that laid bare the nature of light for all to see, but rather through a confluence of different factors, by the end of the nineteenth century, physicists were convinced beyond the shadow of a doubt that light is a wave. This conclusion was well supported both by key experimental findings (e.g., diffraction and interference effects) and by a remarkable and profound theoretical achievement. In the 1860s, the physicist James Clerk Maxwell proposed a unified field theory of electric and magnetic phenomena, through which it was possible to actually *derive* (rather than merely postulate) the wave nature of light.[2] At long last, after centuries of debate about the nature of light, the matter seemed to be settled once and for all: light is a wave.

Confidence in this solidly ensconced view was not easily shaken despite the initially mild rumblings beneath the surface that contrary evidence was emerging from the nascent research area of atomic physics in the early twentieth century.[3] It was not merely that new empirical evidence concerning the nature of light seemed to contradict the established view, but during the first quarter of the twentieth century, it became increasingly difficult to understand how *any* consistent understanding of the nature of light would be possible. It was quite uncanny: the new experiments seemed to indicate that light manifests particle-like characteristics under one set of experimental conditions and wavelike characteristics under other circumstances. If this wasn't puzzling enough, evidence that *matter* exhibited this same dual "wave-particle" feature followed in short order: matter could exhibit wave behavior as well as (the classically expected) particle behavior (under complementing circumstances). Wave-particle duality seemed to be a feature of both light and matter. So profound were these results that even in the face of the enormous and far-reaching successes of electromagnetic theory (which proved to be completely consistent with Einstein's special theory of relativity), these subterranean rumblings, coming out of the new experiments using small quantities of light and matter, eventually reached up to the surface and shook the very foundations of Newtonian physics.[4]

These findings seemed to indicate nothing less than a seismic shift in our understanding of the nature of scientific knowledge, if not the very nature of the world. Before the early years of the twentieth century, it seemed that everything could be sorted neatly into the distinct categories of waves and particles. Each "bit" of nature had a distinct identity that landed it a place in one column or the other. After all, waves and particles are distinct phenomena with mutually exclusive characteristics. Particles are localized objects that occupy a given location at each moment in time. Waves have an entirely different nature: they are not even properly entities but rather disturbances in some medium or field.[5] Waves have extension in space, occupying more than one position at any moment of time, like ocean waves that move along a stretch of beach; and furthermore, waves can overlap (i.e., interfere) with one another and occupy the same position at any moment of time, unlike particles. The dual nature of light and matter presented a quandary of the first order: an object is either localized or extended; it can't be both.[6]

In an effort to try to gain a deeper understanding of the underlying physics, physicists sometimes turn to *gedanken* (thought) experiments. Gedanken experiments are pedagogical devices. They are tools for isolating and bringing into focus key conceptual issues. Generally speaking, there is no expectation that a gedanken experiment will ever be realized as an actual laboratory experiment. Einstein and Bohr made famous and extensive use of gedanken experiments in trying to get at the essential elements of the physics. Indeed, gedanken experiments became the testing ground for their contrary understandings of quantum physics.[7]

With the wave-versus-particle nature of light (and matter) at stake, yet again, it is perhaps not surprising that physicists turned to the two-slit experiment associated with Thomas Young. As discussed in chapter 2, a two-slit experiment can be used to test whether the phenomenon in question

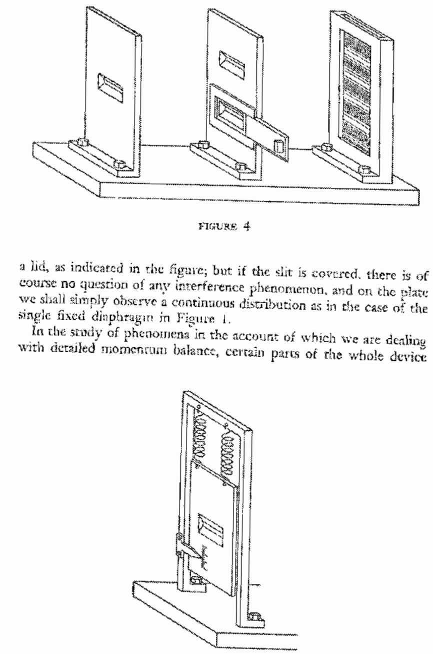


FIGURE 4

a lid, as indicated in the figure; but if the slit is covered, there is of course no question of any interference phenomenon, and on the plate we shall simply observe a continuous distribution as in the case of the single fixed diaphragm in Figure 1.

In the study of phenomena in the account of which we are dealing with detailed momentum balance, certain parts of the whole device

FIGURE 5

8 A page from Bohr's *Atomic Physics and Human Knowledge* showing figures 4 and 5, his two sketches related to the famous two-slit gedanken experiment. Notice the detailed nature of Bohr's diagrams. Bohr went to the trouble of drafting diagrams of gedanken experiments with great attention to detail (e.g., the bolts that hold the diaphragm to the platform). For Bohr, the precise details of the apparatus mattered for reasons that will soon become apparent. *From Niels Bohr,* Atomic Physics and Human Knowledge, *vol.* 2 *(1963),* 48. *Reprinted with permission of Ox Bow Press, Woodbridge, Connecticut.*

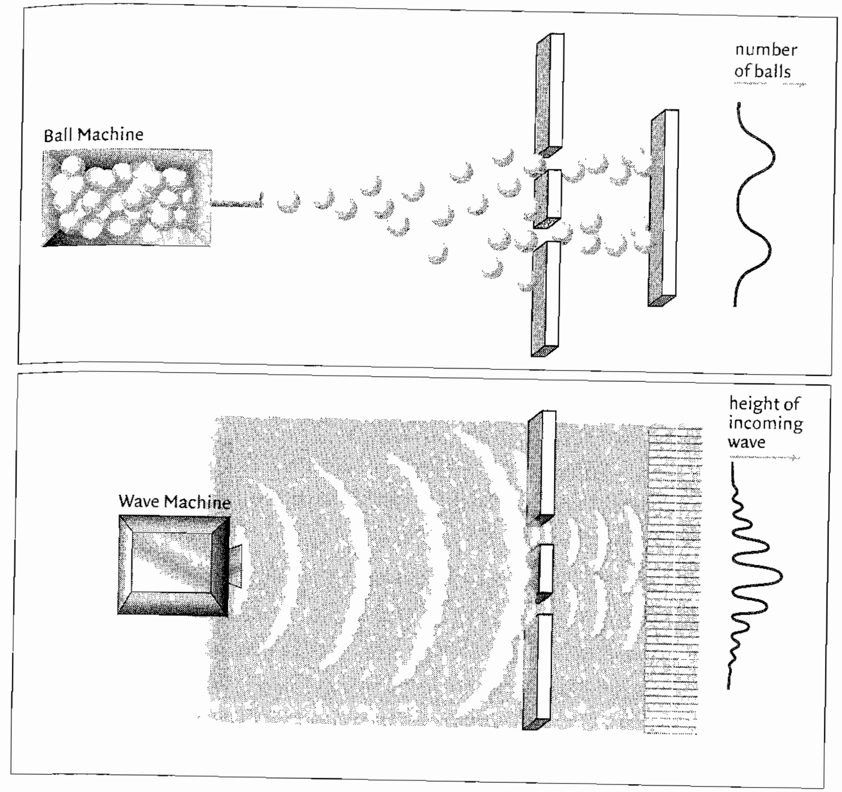
is a wave or a particle, since waves and particles leave distinctive patterns of marks on the screen. Bohr and Einstein made creative use of the two-slit gedanken experiment and suitable modifications to explore a host of quantum quandaries. Bohr's papers include many detailed drawings of the apparatus in question. Figure 8 shows Bohr's rendition of a particular version of the two-slit experiment he discussed with Einstein. Note the significant amount of detail in his drawings. This may seem strange at first glance, given that these are drawings of instruments used to "perform" thought experiments, not actual experiments to be realized in the laboratory. But as we will see, the apparatus is of great significance in these discussions.

From the perspective of classical mechanics, the two-slit experiment evidences a stark distinction between particle and wave behaviors. When particles are aimed at the partition with the double slits, we find that most of the particles land on the detection screen directly opposite each of the two openings in the partition (figure 9, top diagram), with a smaller number scattering off to either side. The bimodal pattern to the far right is a graphical representation of this result: it indicates the number of particles that are collected at each location along the screen and shows that the bulk of particles are found directly across from the slits. Waves, on the other hand, exhibit a very different pattern (figure 9, bottom diagram). When waves impinge on a barrier with two openings, they spread out as they emerge from each of the slits. The emerging waves interfere with one another (like the pattern one sees when watching two stones splash into a pond simultaneously). When the interfering waves reach the screen, the greatest intensity will be at the centerline between the two openings (as discussed in chapter 2). As one moves off to the sides, the resulting wave amplitude alternates from areas of constructive interference (high intensity, e.g., bright lines) to areas of destructive interference (low intensity, e.g., dark lines). This overall pattern exhibited by waves is called an interference or diffraction pattern.

Now, the question is, what happens if we perform this experiment using electrons? The surprising—indeed, startling—result is that electrons, tiny particles of matter, produce a diffraction pattern (figure 10)! How can this be? Why don't we get a pattern characteristic of particles? How can we understand this astonishing result?

Are the electrons somehow "interfering" with one another? We can in fact eliminate this possibility (and it's not even clear what it means) by sending each electron through one at a time. That is, we fire one electron at a time at the double slits and wait until it hits the detection screen before sending the next one. Now there is no chance of the electrons interacting, let alone "interfering," with one another. What do we see after sending the first particle through? We find a single mark on the detection screen indicating the position of the electron as it arrived at the screen. So far this seems to follow our classical-physics intuition that electrons are little particles. This happens for each and every electron run that is collected: each electron arrives at a well-defined location on the screen. But here's the rub: we collect the data for each event, and look at the overall pattern after a large number of electrons have gone through, and what do we observe? An interference pattern—the electrons manifest wave behavior! But how is this possible? Unlike the case of water waves, which go through both slits at once, the electrons are sent through one at a time. Does an *individual* electron "interfere" with itself? Does a *single* electron somehow go through *both* slits at once? How can this be? Doesn't each electron go though one slit or the other?[8]

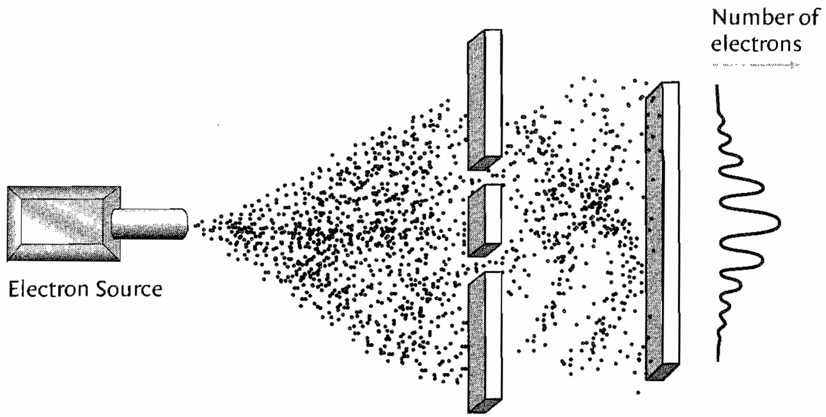
Suppose we alter the apparatus in such a way that we can detect which slit an individual electron passes through on its way to the screen. Einstein and Bohr discussed several possible apparatuses that could be used to detect



9 Two-slit experiments for particles (*top*) and waves (*bottom*). The diagram summarizes the results expected from the point of view of classical physics and emphasizes the differences in wave and particle behaviors. The particle experiment (*top*) is conducted using a ball machine as the source and a detection screen to the right that records where each ball lands on the screen. The wave experiment (*bottom*) uses water waves, and the dock to the right serves as a detection screen that measures the amplitude of the incoming waves. The graph to the right of the experiment using particles (*top*) shows that most of the balls or particles are detected directly opposite each of the slits, with some going off to either side. By contrast, the graph of the results of the wave experiment (*bottom*) shows a characteristic diffraction or interference pattern. *Illustration by Nicolle Rager Fuller for the author.*

"which-slit," or what is more commonly called "which-path," information. Figure 11 shows Bohr's two-slit apparatus, including a modification that enables a determination of which-path values.[9]

The idea behind this clever modification is that if the electron goes through the upper slit, it will displace the diaphragm on springs (resulting from a transfer of momentum of the electron to the diaphragm as it passes through the slit), and this displacement can be measured. Hence, by watch-

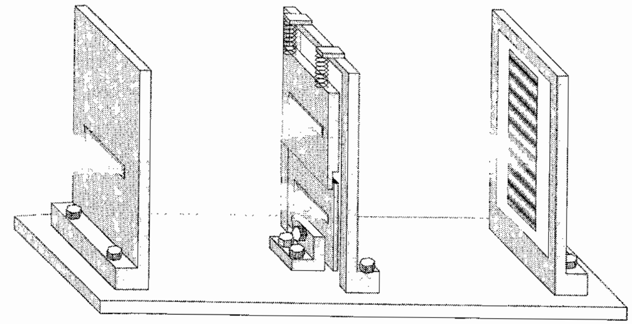


10 Two-slit experiment for electrons. Even though each electron leaves an individual mark on the detection screen, the observed diffraction interference pattern is characteristic of wave behavior. *Illustration by Nicolle Rager Fuller for the author.*

ing the displacement of the diaphragm, we could determine whether a given electron had gone through the upper slit or the lower one. Any particle worth its salt goes through one slit or the other on its way to the detecting screen. So it seems that by using this device, it should be possible to catch electrons in the act of behaving like a particle and a wave simultaneously. In fact, this is what Einstein predicted, and it was the reason he proposed the experiment as part of his larger effort to expose the inherent inadequacy of the quantum theory. (Despite his Nobel Prize–winning conjecture that light can behave as a particle, Einstein was one of the few holdouts against the quantum revolution; he died without fully embracing quantum mechanics.)

What do we find? Bohr argued that if we were to perform a two-slit experiment with a which-path device (which can be used to determine which slit each electron goes through on its way to the detecting screen), we would find that the interference pattern is destroyed. That is, if a measurement is made that identifies the electron as a particle, as is the case when we use a which-path detector, then the result will be a particle pattern, not the wave pattern that results when the original unmodified two-slit apparatus is used. But this result makes the situation even more confusing than ever—is the electron a particle or a wave? How can we get different results using different experimental apparatuses?

Let's pause for a moment to take in the fact that although this "experi-



11 Bohr's two-slit interference device with a which-path detector. For details, see the caption for figure 6. *From P. Bertet et al., "A Complementarity Experiment with an Interferometer at the Quantum-Classical Boundary," Nature* 411 (2001): 167, figure 1. Reprinted with permission of Macmillan Publishers Ltd.

mental result" is what often gets reported as a simple matter of fact in both pedagogical and popular accounts, the fact is that we've been talking about a gedanken experiment, not an actual experiment. So what's going on here? What's being reported is not actual data but a prediction based on theoretical arguments. The reported result is Bohr's *prediction* for what would occur *if* we were (able) to perform the experiment.

It is a remarkable and quite unexpected fact that in the mid-1990s it became technologically possible to *actually perform* a version of this gedanken experiment in the lab (see chapter 7).[10] That is, well after the deaths of Einstein and Bohr, after years of debate concerning the outcome of this gedanken experiment, we now know what happens if we do perform the experiment in a lab. (Check out chapter 7 to find out what happens!) Knowing all of this, it seems prudent to back up and examine the issues and their implications more closely before we attempt to figure out what the results mean.

How did Bohr come to such a conclusion? Bohr arrived at this conclusion only after wrestling long and hard with the paradox of wave-particle duality. He set his sights on trying to find a logically coherent explanation amid all this confusion. The anchor point that Bohr used to steady the sense of vertigo that accompanied these perplexing results was that the (actual) experiments that displayed the "dual" nature of matter and light were both consistent and reproducible: every time a given apparatus was used, the same behavior—whether particle or wave (not both)—resulted. One apparatus consistently manifested one kind of behavior, and a mutually exclusive apparatus consistently exhibited another. Bohr argued that if we are clear about what we mean by the notions of "wave" and "particle," it would be impossible to find electrons behaving like particles and waves simultaneously. In fact, Bohr insisted that if it were possible to obtain which-path information and maintain the wave (interference) pattern, physics would have a real crisis on its hands because this would call into question the possibility of a logically consistent theory. For Bohr, the crucial point is the fact that wave and particle behaviors are exhibited under *complementary*—that is, *mutually exclusive*—circumstances. According to Bohr, either we can find out which slit an electron goes through by using the which-path apparatus, in which case the resulting pattern will be that which characterizes particles, *or* we can forgo knowledge about which path the electron goes through (using the original unmodified two-slit apparatus) and obtain a wave pattern —we can't have it both ways at once.

In some important ways, this all seems very sensible, but the implications are nothing short of revolutionary. Notice what the complementary nature of these results means: *the nature of the observed phenomenon changes with corresponding changes in the apparatus.* But this is contrary both to the ontology assumed by classical physics, wherein each entity (e.g., the electron) is either a wave or a particle, independent of experimental circumstances, and to the epistemological assumption that experiments reveal the preexisting determinate nature of the entity being measured. Bohr's conclusion, as we will see, is that classical physics, along with the classical epistemological and ontological assumptions on which it is based, is fundamentally flawed.

MEASUREMENT MATTERS: BOHR'S EPISTEMOLOGICAL FRAMEWORK

Classical epistemological and ontological assumptions, such as the ones found to underlie Newtonian physics, include the existence of individual objects with determinate properties that are independent of our experimental investigations of them. This accounts for the fact that the process of measurement is transparent and external to the discourse of Newtonian science. It is assumed that objects and observers occupy physically and conceptually separable positions. Objects are assumed to possess individually determinate attributes, and it is the job of the scientist to cleverly discern these inherent characteristics by obtaining the values of the corresponding observation-independent variables through some benignly invasive measurement procedure. The reproducibility of measured values under the

methodology of controlled experimentation is used to support the objectivist claim that what has been obtained is a representation of intrinsic properties that characterize the objects of an observation-independent reality.[11] The transparency of the measurement process in Newtonian physics is a root cause of its value to, and prestige within, the Enlightenment culture of objectivism.

Bohr called into question two fundamental assumptions that support the notion of measurement transparency in Newtonian physics: (1) that the world is composed of individual objects with individually determinate boundaries and properties whose well-defined values can be represented by abstract universal concepts that have determinate meanings independent of the specifics of the experimental practice; and (2) that measurements involve continuous determinable interactions such that the values of the properties obtained can be properly assigned to the premeasurement properties of objects as separate from the agencies of observation. In other words, the assumptions entail a belief in representationalism (the independently determinate existence of words and things), the metaphysics of individualism (that the world is composed of individual entities with individually determinate boundaries and properties), and the intrinsic separability of knower and known (that measurements reveal the preexisting values of the properties of independently existing objects as separate from the measuring agencies). Let's examine the role of these assumptions in detail and consider Bohr's specific challenges to them.

The hallmark of Newtonian physics is its strict determinism: given the "initial conditions" (i.e., the position and momentum of a particle at any one instant in time) and the full set of forces acting on a particle, the particle's entire trajectory (i.e., its entire past and future) is determined. Newton's equations (i.e., the laws of classical mechanics) are acclaimed for their ability to predict and retrodict the physical state of a system for all time. According to Newtonian mechanics, the initial conditions can be determined by any one of a number of different measurement procedures.

One technique for determining the initial conditions is the so-called time-of-flight measurement. According to this technique, the simultaneous position and momentum values of an object can be determined by bouncing electromagnetic radiation (or light) off the object and detecting it with a detector. (This is the basic principle behind the laser radar gun, commonly used to detect the speed of cars and tennis balls.) It is important to note that since light has momentum and energy, the measurement *necessarily* disturbs the object.[12] The fact that things are disturbed when we measure them is not a startling new result of quantum physics—this point already follows from classical physics. However, when time-of-flight measurements are made on everyday objects, this fact is often ignored. This is because when light bounces off a relatively large object, the disturbance it imparts is negligible relative to the accuracy of the measurement. That is, it is often the case that any such disturbance is too small to notice. (For example, we don't notice the furniture being rearranged in the room when we turn a light on in a dark room, although this is strictly the case.) There are, however, situations in which the disturbance is noticeable (e.g., when the accuracy of the measurement is increased beyond a certain limit or when the object is sufficiently small). But Newtonian physics is not troubled by this scenario, either. When the disturbance is not negligible, Newtonian physics argues that the measurement-independent values of the object's position and momentum can be found nonetheless because the disturbance can always be determined and subtracted out. According to Niels Bohr, this account of the measurement process rests on false assumptions.

Bohr's criticism of measurement transparency is based on two important points: the discontinuity and the indeterminacy of measurement interactions. According to Bohr, at the beginning of the twentieth century a crucial empirical fact was discovered that disproves the classical assumption that measurement interactions are continuous. This "essential discontinuity"—or "quantum jump"—characterizes quantum physics. Despite its common colloquial usage to mark a large (discontinuous) change, a quantum jump is not large at all—in fact, the term "quantum" means the smallest quantity or discrete amount that exits.[13] In fact, this essential discontinuity is otherwise known in physics as Planck's constant (after its founder), symbolized by h, and it is indeed an extremely small quantity.[14] This idea of an essential discreteness or discontinuous nature was initially introduced by Max Planck in 1900 in his attempt to account for some data on blackbody radiation, which would not yield to classical physics analysis. In particular, he proposed that energy is "quantized" and exchanged in discrete amounts. The fact that $h \neq 0$ (i.e., that the value of Planck's constant is not zero) marks the existence of a fundamental discontinuity of nature.[15] The failure of Newtonian physics to take appropriate account of this discontinuity portends its downfall.

The lack of continuity places a lower bound on how small the disturbance caused by the measurement interaction can be (e.g., the light can be reduced in its intensity no further than one "photon"—one particle of light—or else no measurement takes place). In particular, it means that Newtonian physics will have to face the limits of its ability to ignore measurement interactions

by presuming that they can always be reduced to the point where they are negligible. Hence, the only remaining possibility, if the goal is to determine the presumed measurement-independent properties of an object, is to determine the effects of the measurement interaction.

This brings us to the crux of Bohr's contribution. Bohr argues that it is impossible to determine the effect of a measurement interaction and have it serve the purpose it was designed for (presumably to measure some particular quantity), and hence the assumption of measurement transparency is false. But why is this determination prohibited?

Bohr's argument for the indeterminable nature of measurement interactions is based on his insight that *concepts are defined by the circumstances required for their measurement.*[16] That is, *theoretical concepts* are not ideational in character; they *are specific physical arrangements.*[17] For Bohr, measurement and description (the material and the discursive) entail each other (not in the weak sense of operationalism but in the sense of their mutual epistemological implication).[18] Bohr argues that because concepts, like "position" and "momentum," for example, are specifically embodied, mutually exclusive experimental arrangements need to be employed simultaneously (which is by definition impossible) to determine all the required features of the measurement interaction. This is best explained by way of example.

Consider the measurement of the position of a particle. This basic example is sufficient to bring the key issues to the fore. In particular, it will help us to understand some crucial features of the measurement process. The insights that we will gain about the nature of measurement interactions will not depend on the fact that we are measuring position per se, as opposed to some other variable, or that the object we have chosen is a particle.[19] As in any good gedanken experiment, these choices are made to help us focus on the important features. The choice of the measurement of position is advantageous for at least two reasons. First of all, position is one of the key variables in physics—it is in fact one of the two variables (the other being momentum) required for the specification of the initial conditions in Newtonian mechanics. Furthermore, position is a concept that has an intuitive sense to it (as opposed to momentum, for example), and there are straightforward and intuitive approaches to measuring it. The choice of a particle, as opposed to, say, a baseball, has to do with the fact that we are more inclined to be attentive to certain details that one might skip over in thinking about the measurement of an everyday object.[20]

There is a common misconception (shared by some physicists as well as the general public) that quantum considerations apply only to the micro world. Some people think that the fact that *h* is very small means that the world is just as Newton says on a macroscopic scale. But this is to confuse practical considerations with more fundamental issues of principle. No one would suggest that because atoms are too small to see with the naked eye, we are therefore entitled to deny their existence and their relevance to our everyday lives (although we do at times successfully ignore their existence). The entity in question may be small, but its consequences may be quite profound. This is indeed true of the existence of the fundamental discontinuity. As we will see from the analysis that follows, the key point is the very existence of the essential discontinuity, not its size. To the best of our knowledge, *h* is a universal *constant*. In particular, as far as we know, it is not zero anywhere: or under any circumstances. (For example, there doesn't seem to be any cutoff point beyond which *h* is strictly equal to zero.) And this is the point. Bohr's analysis does not depend on the size of *h*, only the fact that it is nonzero.

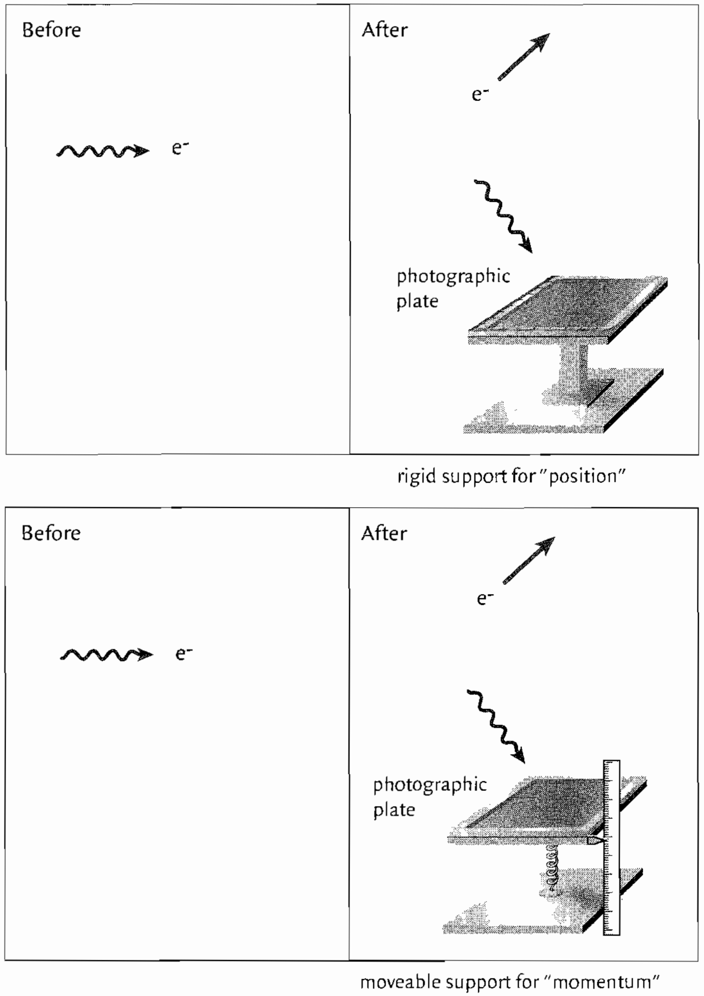
This point, which has so often been misunderstood, bears repeating. The fact that *h* (Planck's constant) is small relative to the mass of large objects does *not* mean that Bohr's insights apply only to microscopic objects. It does mean that the effects of the essential discontinuity may be less evident for relatively large objects, but they are *not* zero. To put it another way, no evidence exists to support the belief that the physical world is divided into two separate domains, each with its own set of physical laws: a microscopic domain governed by the laws of quantum physics, and a macroscopic domain governed by the laws of Newtonian physics. Indeed, quantum mechanics is the most successful and accurate theory in the history of physics, accounting for phenomena over a range of twenty-five orders of magnitude, from the smallest particles of matter to large-scale objects.[21] Quantum physics does not merely supplement Newtonian physics—it supersedes it.[22] The key point is this: Bohr's analysis of the nature of measurement interactions and the epistemological implications of his analysis are completely general (as far as we know). In particular, they are *not* limited to the microscopic domain.

Let's proceed with our gedanken experiment. All that we need to measure the position of a particle is a flash camera mounted on a tripod and a dark room. Let's look at each of the components of the experimental setup in turn: we need a dark laboratory, since light imparts momentum to objects that it impinges on and we want the particle to be disturbed as little as possible; we need a camera or photographic plate or film for recording the position of the object; we need a flash or some light source for illuminating

the object during the position measurement (that is, while its picture is being taken); and we need a tripod or some other rigid support for steadying the recording device (e.g., the photographic plate) so that the picture won't be blurred. More details follow. Note that since the aim of this gedanken experiment is to understand where the Newtonian assumptions fail, I will use the language of classical mechanics (which, for example, assumes that objects have individually determinate properties before the act of measurement and that the measurement interaction disturbs the prior values) until we more fully understand what an alternative might look (and sound) like.

There are several important features of the position measurement to consider. First, according to Bohr, the concept of position (like all concepts) cannot be taken for granted; rather, it must be defined by the circumstances required for its measurement. In the case we are considering, position is meaningfully defined (semantically determinate) only if the circumstances are such that the photographic plate is *fixed* with respect to the laboratory frame of reference—this is where the tripod comes in handy. This is necessary because if we were to allow the plate to move during the measurement, we would not have a viable way of defining the particle's position; indeed, it would be indeterminate. (If we were to hold the shutter of a camera open and move it around while taking the picture, the photograph would surely be blurred and would not give us any meaningful indication of an object's position.)[23] By contrast, the concept of momentum is well defined only if the circumstances are such that the apparatus consists of *movable* parts.[24] In the example we are considering, this means that the photographic plate or camera would have to rest on a movable platform rather than a fixed one. This is necessary because it is only by measuring how much the platform moves back in absorbing the momentum transfer (if the momentum is large, the displacement of the plate will be large, and if the momentum is small, the displacement will be small) that any meaningful indication of an object's momentum can be ascertained. However, if the platform is fixed, the momentum will be absorbed, and its value will be indeterminate. Hence a measurement of the displacement of the platform can be calibrated to give an accurate readout of "momentum" if and only if a movable platform supports the photographic plate or camera, in which case the momentum value will be determinate. Crucially, then, *the position and momentum are not simultaneously determinate because they require mutually exclusive experimental circumstances* (a fixed support and a movable support respectively; see figure 12).

Figure 12 shows a schematic of our gedanken experiment. Notice that the diagram indicates a single photon impinging on the particle. This is the



2 This drawing illustrates Bohr's principle that theoretical concepts are defined by the physical circumstances required for their measurement. The diagrams show the respective embodiments of complementary concepts: "position" (*top*) and "momentum" (*bottom*). The important point illustrated here is that position is determinate if and only if it is measured using an apparatus with a fixed platform (*top*), while momentum is defined by an apparatus with movable platform (*bottom*). (Note that the momentum-measuring apparatus is simplified for pedagogical purposes; it shows only the measurement of momentum in one direction, along the axis indicated by the ruler, let's call it the z-direction. When the photon hits the plate, the spring is compressed in proportion to its incoming momentum in the z-direction. To measure the full momentum vector would require an apparatus with movable parts and measuring devices in all three directions, that is, movement in the plane of the photographic plate, the x- and y-directions, in addition to the movement perpendicular to it.) *Illustration by Nicolle Rager Fuller for the author.*

best-case scenario given the existence of the quantum discontinuity. That is, we need at least one photon to perform a measurement, and yet this is still sufficient to disturb the particle's position. So the only possibility for determining the (presumed) measurement-independent value of the particle's position is to determine the effect of the measurement interaction. In other words, we are now ready to face the situation we want to investigate.

How can we determine the effect of the measurement interaction? Suppose we already know the initial momentum of the photon (as it leaves the camera's flash). If we could measure the final momentum of the photon after it impinges on the object, then we would know the photon's change in momentum. This would be extremely useful because the change in the particle's momentum is clearly the direct result of the measurement interaction and must therefore be related to the change in the photon's momentum. In fact, the law of the conservation of momentum provides us with a quantitative statement of this "transfer" of momentum: the change in the particle's momentum (vector) is equal (and opposite) to the change in the photon's momentum (vector). Therefore, using the law of conservation of momentum, we can calculate the change in the particle's momentum once we know the photon's momentum change. So we need to measure the photon's momentum after it impinges on the object. But as we saw earlier, a measurement of the photon's momentum requires a *movable* platform. But this is excluded by the requirement for the measurement of the position (of the photon on the photographic plate, which marks the position of the particle in the room): position, as we saw, is necessarily defined by reference to a *fixed* platform. Hence it is not possible to determine the effect of the photon on the particle, since we would need to determine the photon's position and momentum simultaneously, which is physically impossible given that the measurements of position and momentum require mutually exclusive apparatuses for their respective determination. Therefore we arrive at Bohr's conclusion: *observation is only possible on the condition that the effect of the measurement is indeterminable*. Now, the fact that the measurement interaction is indeterminable is crucial because it means that we can't subtract the effect of the measurement and thereby deduce the properties that the particle (is presumed to have) had before the measurement. This does not mean that we can't measure position accurately; indeed, we can (we just use an apparatus with fixed parts). What it *does* mean is that we are *not* entitled to ascribe the value that we obtained for the position to some abstract notion of a measurement-independent object (i.e., the object as it presumably would have been before the measurement). So what does the value correspond to?

What is the objective referent? Shall we conclude that the measurement interaction produced the value we obtained? If so, would we not be hard pressed to even speak of this interaction as a "measurement"? Vertigo threatens once again. Back to Bohr.

Bohr argues that the indeterminacy of the measurement interaction is of profound consequence: Since observations involve an indeterminable discontinuous interaction, *as a matter of principle, there is no unambiguous way to differentiate between the "object" and the "agencies of observation."* No inherent/Cartesian subject-object distinction exists. This aspect of Bohr's analysis can be demonstrated if we turn our attention once again to our gedanken experiment. As previously noted, as the scattered photon approaches the photographic plate, it may encounter one of two possible mutually exclusive arrangements: if the photographic plate is supported by a fixed platform, a determinate value can be obtained for its position, and if the platform is movable, a determinate value can be obtained for its momentum.[25] The first case essentially describes the process of taking a picture of a particle with a flash camera. In that case, the light (photon) is part of the *agencies of observation*. In the latter case, the light's (photon's) momentum is being measured, and hence it is part of the *object* in question. So the question of what constitutes the object of measurement is not fixed: as Bohr says, there is no inherently determinate Cartesian cut. *The boundary between the "object of observation" and the "agencies of observation" is indeterminate in the absence of a specific physical arrangement of the apparatus.* What constitutes the object of observation and what constitutes the agencies of observation are determinable only on the condition that the measurement apparatus is specified. *The apparatus enacts a cut delineating the object from the agencies of observation.* Clearly, then, as we have noted, *observations do not refer to properties of observation-independent objects (since they don't preexist as such).*

Notice also that along the way we have confirmed another one of Bohr's claims: *the measurement interaction can be accounted for only if the measuring device is itself treated as an object, defying its purpose as a measuring instrument.* This follows from the fact that while the measurement of position (using an apparatus with a fixed platform) constitutes the photon as part of the agencies of observation, the measurement of its momentum (using an apparatus with a movable platform) would constitute the photon as the object of observation. It can't serve as object if it is to perform its intended duties as part of the agencies of observation.

If the distinction between object and agencies of observation is not inherent, what sense, if any, should we attribute to the notion of observation? Bohr suggests that "by an experiment we simply understand an event about which we are able in an unambiguous way to state the conditions necessary for the reproduction of the phenomena" (quoted in Folse 1985, 124).[26] The specification of the conditions necessary for an unambiguous account of quantum phenomena is tantamount to *the introduction of a constructed, agentially enacted, materially conditioned and embodied, contingent Bohrian cut between an object and the agencies of observation.*[27] That is, although no inherent distinction exists, every measurement involves a particular choice of apparatus, providing the conditions necessary to give meaning to a particular set of variables, at the exclusion of other essential variables, thereby placing a particular embodied cut delineating the object from the agencies of observation. So for every given apparatus, there is an unambiguous resolution of the distinction between the object and the agencies of observation. This much bodes well for holding on to some notion of objectivity despite the productive role that human artifacts such as apparatuses and concepts seem to play. But before we proceed further in this direction, we need to understand the nature of this role better. This will help us in our quest to identify the referent for the measured properties.

As part of this quest, it is instructive to consider important differences between Niels Bohr's and Werner Heisenberg's views on the nature of the measurement process and its implications. Turning our attention to this matter will help distill some of Bohr's most fundamental thinking on these issues.

INDETERMINACY VERSUS UNCERTAINTY

The time-of-flight example discussed in the previous section has some essential features in common with the "Heisenberg microscope" experiment. Heisenberg considers this latter gedanken experiment in his paper that introduces his famous "uncertainty principle." As I discussed in the introduction, Bohr developed complementarity, his alternative epistemological framework, at the same time that Heisenberg came up with the uncertainty principle. Although it is often said that complementarity and uncertainty are the cornerstones of the Copenhagen interpretation, the fact is that these respective contributions constitute fundamentally different, indeed arguably incompatible, interpretative positions. When Heisenberg showed his uncertainty paper to Bohr, Bohr complained that the paper contained a fundamental error. Heisenberg acquiesced and added a postscript to his paper that acknowledges the flaw in his reasoning: "Bohr has brought to my attention that I have overlooked essential points in the course of several discussions in this paper."[28] While the immense fame of the uncertainty principle has overflowed from physics into the popular culture, few seem to even be aware of the existence of this postscript or its import. More importantly, the physics community seems to have forgotten it. A similarly significant and underappreciated fact is that Bohr introduced an "indeterminacy principle" as part of his larger complementarity framework that can usefully be contrasted with Heisenberg's uncertainty principle (see chapter 7).[29] In this section I examine the contrasting analyses and interpretations of Bohr and Heisenberg.[30]

In Heisenberg's famous 1927 paper on the uncertainty relations, he considers the measurement of the position of an electron using a γ-ray (i.e., gamma-ray or high-energy photon) microscope. This gedanken experiment considers the detection of an electron by a photon. The similarity of this experiment to the one we just considered provides an excellent opportunity for comparing the analyses of Bohr and Heisenberg. According to Heisenberg, the important issue is that

> the highest attainable accuracy in the measurement of position is governed by the wavelength of the light. However, in principle one can build, say, a γ-ray microscope and with it carry out the determination of position with as much accuracy as one wants. In this measurement there is an important feature, the Compton effect [i.e., the scattering of a photon from an electron]. . . . At the instant when position is determined—therefore, at the moment when the photon is scattered by the electron—the electron undergoes a discontinuous change in momentum. This change is greater the smaller the wavelength of the light employed—that is, the more exact the determination of the position. At the instant at which the position of the electron is known, its momentum therefore can be known up to magnitudes which correspond to that discontinuous change. Thus, the more precisely the position is determined, the less precisely the momentum is known, and conversely. (Quoted in Wheeler and Zurek 1983, 64)

In other words, according to Heisenberg's analysis, the key issue is the discontinuous change in the electron's momentum, that is, the fact that it is *disturbed* by the photon in the attempt to determine the electron's position. This analysis, based on the notion of *disturbance*, leads Heisenberg to conclude that the uncertainty relation is an *epistemic* principle—it says there is a limitation to what we can *know*. In other words, a determinate value of the electron's momentum is assumed to exist independently of measurement, but we can't know it; we remain *uncertain* about its value, owing to the unavoidable disturbance caused by the measurement interaction. Notice that

Heisenberg's analysis stops just at the point where Bohr's begins: the existence of a disturbance is an important point; however, this fact alone does not exhaust the possibilities for determining the (alleged) preexisting properties of the particle because it may be possible to determine the effect of the measurement interaction and subtract its effect. This latter point forms the crux of Bohr's analysis and is the basis for his objection against Heisenberg's derivation. While Heisenberg's sole focus is on the discontinuity entailed in measurement interactions, Bohr introduces a second, arguably more fundamental, issue: that of the conditions of possibility for determining the effect of the measurement interaction. For Bohr, the analysis of these conditions rests on the crucial insight that concepts are meaningful, that is, semantically determinate, not in the abstract but by virtue of their embodiment in the physical arrangement of the apparatus. Bohr makes clear that this point calls into question Heisenberg's epistemic interpretation:

> It must here be remembered that even in the [uncertainty] relation we are dealing with an implication of the formalism which defies unambiguous expression in words suited to describe classical physical pictures. Thus, a sentence like "we cannot know both the momentum and the position of an atomic object" *raises at once questions as to the physical reality of two such attributes of the object*, which can be answered only by referring to the conditions for the unambiguous use of space-time concepts, on the one hand, and dynamical conservation laws, on the other hand. While the combination of these concepts into a single picture of a causal chain of events is the essence of classical mechanics, room for regularities beyond the grasp of such a description is just afforded by the circumstance that the study of the complementary phenomena demands mutually exclusive experimental arrangements. (Bohr 1963b [1949 essay], 40–41; my emphasis)

In other words, Bohr argues that one is not entitled to ascribe an independent physical reality to these properties, or, for that matter, to the notion of an independently existing object.

Heisenberg's analysis thus misses the crucial question of how the cut gets made and the indeterminacy is resolved. As I mentioned, Bohr expressed his disapproval of Heisenberg's derivation, and Heisenberg acquiesced to Bohr's point of view and added a postscript to his article on the uncertainty principle, in which he states:[31]

> In this connection Bohr has brought to my attention that I have overlooked essential points in the course of several discussions in this paper. Above all, the uncertainty in our observation does not arise exclusively from the occur-

rence of discontinuities, but is tied directly to the demand that we ascribe equal validity to the quite different experiments which show up in the corpuscular theory on one hand, and in the wave theory on the other hand [i.e., that we acknowledge complementarity, that is, the necessity of considering mutually exclusive experimental conditions].[32] (Quoted in Wheeler and Zurek 1983, 83)

It is unfortunate that this crucial postscript to Heisenberg's paper has (for the most part) been forgotten and its implications lost. The fact remains that the common public conception of the uncertainty principle is (at best) the epistemic version that Heisenberg himself retracted. But even more unfortunate, surely, is the fact that many physics textbooks, physics students, and professional physicists share this misconception.[33]

For Bohr, the real issue is one of *indeterminacy*, not uncertainty (see the detailed discussion in chapter 7). He understands the reciprocal relation between position and momentum in *semantic* and *ontic* terms, and only derivatively in epistemic terms (i.e., we can't know something definite about something for which there is nothing definite to know). Bohr's indeterminacy principle can be stated as follows: *the values of complementary variables (such as position and momentum) are not simultaneously determinate.*[34] The issue is not one of unknowability per se; rather, it is a question of what can be said to simultaneously exist.

PHENOMENA

As we have seen, for Bohr the central issue concerning the nature of measurement is not one of disturbance but one of resolving an inherent indeterminacy.[35] In other words, in Bohr's account, the key point is "quantum wholeness," or the lack of an inherent/Cartesian distinction between the "object" and the "agencies of observation." In the absence of a given apparatus there is no unambiguous way to differentiate between the object and the agencies of observation: an apparatus must be introduced to resolve the ambiguity, but then the apparatus must be understood as part of what is being described. "*Descriptively*, there is a *single* situation, no part of which can be abstracted out without running into conflict with other such descriptions (namely, those of complementary situation). The object cannot be ascribed an 'independent reality in the ordinary physical sense'" (Hooker 1972, 156; italics in original).

This is a central notion in Bohr's philosophy-physics, and he uses the

term "phenomenon" to designate particular instances of wholeness:[36] "While, within the scope of classical physics, the interaction between object and apparatus can be neglected or, if necessary, compensated for, in quantum physics this *interaction thus forms an inseparable part of the phenomenon.* Accordingly, *the unambiguous account of proper quantum phenomena must, in principle, include a description of all relevant features of the experimental arrangement*" (Bohr 1963c [1958 essay], 4; italics mine). The Bohrian cut *marks off and is part of a particular instance of wholeness, that is, a particular phenomenon.* "The essential wholeness of a proper quantum phenomenon finds logical expression in the circumstance that any attempt at its well-defined subdivision would require a change in the experimental arrangement incompatible with the appearance of the phenomenon itself" (Bohr 1963b [1954 essay], 72). Bohr notes that in this connection he "warned especially against phrases, often found in the physical literature, such as 'disturbing of phenomena by observation' or 'creating physical attributes to atomic objects by measurements.' Such phrases . . . are at the same time apt to cause confusion. . . . As a more appropriate way of expression I advocated the application of the word *phenomenon* exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement" (Bohr 1963b [1949 essay], 63–64).

Bohr insists that quantum mechanical measurements are "objective."[37] Since he also emphasizes the essential wholeness of phenomena, Bohr cannot possibly mean that measurements reveal "objective" (i.e., premeasurement) properties of independent objects. As Bohr says: "It is just arguments of this kind [i.e., the kind we have been considering] which recall the impossibility of subdividing quantum phenomena and reveal the ambiguity in ascribing customary physical attributes to atomic objects" (Bohr 1963b [1949 essay], 51). Rather, Bohr's use of the term "objectivity" is tied to the fact that "no explicit reference is made to any individual observer" (quoted in Murdoch 1987, 99). "Objective" means reproducible and unambiguously communicable—in the sense that "permanent marks . . . [are] left on bodies which define the experimental conditions." Bohr explains:

> Common to the schools of so-called empirical and critical philosophy, an attitude therefore prevailed of a more or less vague distinction between objective knowledge and subjective belief. By the lesson regarding our position as observers of nature, which the development of physical science in the present century has given us, a new background has, however, been created just for the use of such words as objectivity and subjectivity. From a logical stand-

point, we can by an objective description only understand a communication of experience which does not admit of ambiguity as regards the perception of such communications. (Quoted in Folse 1985, 15)

Clearly Bohr's notion of objectivity, which is not predicated on an inherent or Cartesian distinction between objects and agencies of observation, stands in stark contrast to any Newtonian sense of objectivity denoting observation-independence.[38]

In my reading of Bohr, a pivotal point in his analysis is that the physical apparatus, embodying a particular concept to the exclusion of others, marks the subject-object distinction: the physical and conceptual apparatuses form a nondualistic whole marking the subject-object boundary. In other words, concepts obtain their meaning in relation to a particular physical apparatus, which marks the placement of a Bohrian cut between the object and the agencies of observation, resolving the semantic-ontic indeterminacy. *This resolution of the semantic-ontic indeterminacy provides the condition for the possibility of objectivity.* In Bohr's account, objectivity requires accountability to "permanent marks—such as a spot on a photographic plate, caused by the impact of an electron—left on the bodies which define the experimental conditions" (Bohr 1963c [1958 essay], 3). Therefore "bodies which define the experimental conditions" serve as both the endpoint and the starting point for meaningful and objective scientific practice.

The question remains: what is the objective referent for the determinate value of the property measured? Since there is no inherent distinction between object and instrument, the property measured cannot meaningfully be attributed to either an abstract object or an abstract measuring instrument. That is, the measured value is neither attributable to an observation-independent object, nor is it a property created by the act of measurement (which would belie any sensible meaning of the word "measurement"). My reading is that the *measured properties refer to phenomena*, remembering that the crucial identifying feature of phenomena is that they include "all relevant features of the experimental arrangement." To put the point in a more modern context, according to Bohr's general epistemological framework, referentiality must be reconceptualized. The referent is not an observation-independent object but a phenomenon. This shift in referentiality is a condition for the possibility of objective knowledge. That is, *a condition for objective knowledge is that the referent is a phenomenon* (and not an observation-independent object).[39]

Finally, Bohr resolves the wave-particle duality paradox as follows: "wave" and "particle" are classical concepts (that are given determinate meanings by different, indeed mutually exclusive, apparatuses and) that refer to different, mutually exclusive *phenomena*, not to independent physical objects. He emphasized that this saved the theory from inconsistencies, since it was impossible to observe particle and wave behaviors simultaneously because mutually exclusive experimental arrangements are required.

Bohr's epistemological framework is radically different from that associated with Newtonian physics. In fact, Bohr's philosophy-physics undermines a host of Enlightenment notions, requiring him to construct a new logical framework,[40] including a new epistemology, for understanding science. This new interpretative framework, the framework of "complementarity," deviates in a unique and nontrivial fashion from traditional understandings of the nature of scientific practices. Measurement practices are an ineliminable part of the results obtained. Since these practices play a crucial role in the world, they must be a part of scientific theorizing; that is, Bohr situates practice within theory. As a result, method, measurement, description, interpretation, epistemology, and ontology are not separable considerations. I explore these connections in the sections following the methodological interlude.

METHODOLOGICAL INTERLUDE: READING BOHR AND THE INDETERMINACY OF BOHR'S EPISTEMOLOGICAL FRAMEWORK

Many of the philosophers, historians, and the few physicists who have tried to read Bohr's works have commented on the difficulty of the task. Abraham Pais, for instance, wrote that "Einstein once remarked of Bohr, 'He utters his opinions like one perpetually groping and never like one who believes to be in possession of definite truth' " (Pais 1982, 417). Bohr's style is atypical of most science writing. His writing reflects a self-conscious regard of his own descriptive process, which is consistent with his thoroughgoing examination of the role of description in scientific knowledge production, which is fundamental to his approach to understanding quantum physics. Similarly, I have tried to remain attentive to my own descriptive and interpretative process in my reading of Bohr. Consequently I make no claims here to have discovered what Bohr was actually thinking or intending, as separate from my own interpretative apparatus; rather, I attempt to provide a consistent reading, through the consideration of multiple ways of resolving ambiguities. (Recall that for Bohr, descriptions refer to real material phenomena, not to some independent reality.)

My presentation of the major features of Bohr's post-Newtonian framework and corresponding epistemology come from more than two decades of intensive study of Bohr's writings. Interpretative questions about quantum theory plagued me as a graduate student in theoretical particle physics. (It may seem peculiar to nonscientists to discover that physics graduate school is not the appropriate context for engaging such questions.)[41] By the time I was an assistant professor of physics, my focus broadened to include the larger philosophical issues in Bohr's post-Newtonian framework. Tenure provided the opportunity for deeper consideration.

The ideas as I have presented them so far are in considerable agreement with individual features of many of the standard secondary texts on Bohr's philosophy of physics, including the work of Feyerabend (1962), Hooker (1972), Bohm (1985), Folse (1985), Petersen (1985), Honner (1987), Murdoch (1987), and Howard (1994). It is important to point out that the views of these scholars are widely divergent on many crucial points. I do not agree in toto with the views presented in any of these other accounts, though as I read through the primary texts time and again from the perspective of a theoretical particle physicist, various aspects of these works have been and continue to be helpful to me while I formulate my own views on Bohr's philosophy-physics.

As a measure of the disagreement among Bohr scholars, consider the question of the nature of Bohr's interpretative framework. Most Bohr scholars (and many others who have not studied Bohr) attribute some form of antirealism to Bohr, who has been called a positivist, an idealist, an instrumentalist, a (macro)phenomenalist, a relativist, a pragmatist, and a (neo-)-Kantian. The philosopher Henry Folse and I have been the strongest proponents of the minority view that sees Bohr as a realist, though we disagree about the nature of Bohr's realism. John Honner's reading also has realist elements.

One of the major difficulties in resolving the ambiguities in Bohr's position is that he focuses on epistemological issues in his writings and never spells out his ontological commitments. Consequently it is difficult to discern the nature of any correspondence he may hold between theory and reality. Without a clear-cut presentation of a coherent Bohrian ontology, the task of determining what kind of realist or antirealist position is consistent with Bohr's philosophy-physics seems doomed. In the next section, I present an ontology I believe to be consistent with Bohr's views, and I address the question of a correlative interpretative stance.

Furthermore, I argue that another, more far-reaching difficulty in defining Bohr's position is that his philosophy-physics undermines representationalism, which is the basis for various conventional forms of realism and antirealism. Bohr enters the analytical arena at a place before the usual point of entrance in related philosophy-of-science discussions. Bohr begins his analysis with the question of how we should understand the nature of descriptive concepts. Are there specific conditions for their use? What is the correct referent for observational terms? What are the conditions for objective description? Although Bohr's answers to these prior questions undermine representationalism, I will argue that there is an important sense in which Bohr is indeed a realist and that it is worthwhile to retain the term as reconceptualized. In the next chapter, I will provide a further elaboration of this reconceptualized realist view, which I call "agential realism."

As I noted from the outset, my aim is not so much to provide a faithful representation of Bohr's philosophy-physics as to propose a consistent framework for thinking about important epistemological and ontological issues. In addressing these issues, it would be just as dishonest to attribute the full development of this framework to Bohr as it would be to deny that my thinking about Bohr's philosophy-physics is everywhere present in my formulation.

BOHR'S REALIST PRACTICE

Perhaps the most prevalent view concerning Bohr's philosophical stance is that he is a positivist. However, although there have been multiple insinuations and testimonies on behalf of this particular appellation in the literature, this assignment is deeply problematic.[42] Not only is this way of interpreting Bohr not consonant with his philosophical outlook, but it also flies in the face of the way in which Bohr actually practiced science. I will address the former point in what follows. In this section, I focus on the latter.

The realist nature of Bohr's practice is evident in his approach to solving the paradox of wave-particle duality that plagued the old quantum theory. Some antirealists, including Bohr's close colleague Werner Heisenberg, adopted an instrumentalist stance toward the perplexing fact that light and matter exhibit both wave and particle behaviors, resting contentedly with their resolve that the key factor is a working mathematical structure, not a solid conceptual foundation. Conversely, the historical evidence shows that Bohr focused intensely on finding a satisfactory resolution of the conceptual difficulties and was willing to take risky steps and introduce extreme measures in the course of this unwavering effort. Significantly, Bohr cared so deeply about finding a coherent understanding of wave-particle duality that at one point he contemplated the possibility of giving up on perhaps the most fundamental of all physical principles—the conservation of energy and momentum—if in this Faustian bargain he could see his way clear to reconciling the seemingly contradictory findings. In 1924 Bohr wrote a paper with Kramers and Slater putting forth the radical conjecture that the conservation of energy and momentum did not apply at the level of individual atomic events. It is doubtful that an instrumentalist, or some other die-hard antirealist, would have gone to such extremes in trying to make sense of the applicability of mutually exclusive representations. The trio quickly retracted the proposal when contrary experimental evidence came to light demonstrating strict adherence to the conservation laws for individual atomic events, but Slater never forgave Bohr for convincing him to go along with such a radical proposal. The lesson Bohr took from this is the following:

> From these results it seems to follow that, in the general problem of the quantum theory, one is faced not with a modification of the mechanical and electrodynamic theories describable in terms of the usual physical concepts, but with an essential failure of the pictures in space and time on which the description of natural phenomena has hitherto been based. (Bohr 1963a [1925 essay], 34–35)

Interestingly enough, Bohr concludes that what is ultimately at issue is that *quantum theory exposes an essential failure of representationalism.*[43] Indeed, it was Bohr's realist commitment in his practice of science that led him ultimately to adopt a new antirepresentationalist approach for understanding the nature and role of descriptive concepts, which became the basis for his epistemological framework that he called "complementarity," and ultimately the so-called Copenhagen interpretation of quantum mechanics.[44] That is, although a significant number of scholars read the framework of complementarity as an avowedly antirealist philosophy, the historical evidence indicates that the very development of this framework was contingent on certain realist commitments on Bohr's part in his practice of science; otherwise, like some of his instrumentalist contemporaries, he might have been content to let the mathematical formalism "do the talking" (i.e., been satisfied with the fact that calculations based on the formalism agree with the experimental data) and abandoned all efforts to find a viable reconciliation for the problem of the dual nature of light and matter. Bohr was committed to understanding what the science was able to tell us about "that nature of which we are a part." This is a poignant example of how philosophical stances matter in the construction of scientific theories.

A BOHRIAN ONTOLOGY: PHENOMENA AND INTRA-ACTIONS

> Bohr has often been badly misunderstood, I believe, because his readers have insisted on reading the classical ontological and epistemological assumptions into . . . [his] remarks . . . [which] presupposes some autonomously existing atomic world which is describable independently of our experimental investigation of it. There is no such world for Bohr. . . . There is no godlike approach possible to the physical world whereby we may know it as it is 'absolutely in itself'; rather we are able to know only as much of it as can be captured in those situations which we can handle conceptually—that is, those situations where unambiguous communication of the results is possible. . . . This is in complete contrast to the classical realist metaphysics and epistemology where the world is concerned as being the way classical theory says it is, independently of our experimental exploration of it.
>
> —CLIFFORD HOOKER, "The Nature of Quantum Mechanical Reality"

The realism-antirealism distinction is often drawn on the basis of questions about belief in a correspondence theory of truth, which is rooted in subject-object, culture-nature, word-world dualisms. The separation of epistemology from ontology is a reverberation of these dualisms. Bohr's philosophy clearly contests the Cartesian (inherent, fixed, unambiguous) subject-object distinction in a way that undermines the very foundations of classical epistemology and ontology.

Aage Petersen, in an article entitled "The Philosophy of Niels Bohr," writes:

> Traditional philosophy has accustomed us to regard language as something secondary, and reality as something primary. Bohr considered this attitude toward the relation between language and reality inappropriate. When one said to him that it cannot be language which is fundamental, but that it must be reality which, so to speak, lies beneath language, and of which language is a picture, he would reply "We are suspended in language in such a way that we cannot say what is up and what is down. The word 'reality' is also a word, a word which we must learn to use correctly." (Petersen 1985, 302)

Unfortunately Bohr is not explicit about how he thinks we should use the word "reality."

Bohr focuses on crucial epistemological questions such as the conditions for the possibility of objective knowledge, but he does not offer a detailed exposition of the ontological dimensions of his account. It's unfortunate that Bohr does not take up the question of ontology more directly. There is good reason to believe that this would have been enormously helpful in the efforts to settle foundational issues in quantum physics. At the least, it would have provided the conditions for an improved dialogue between Bohr and Einstein, who often talked past each other. But Bohr is not silent about these questions, either. Let's review some of what he does say.

As I noted in the section that discussed Bohr's indeterminacy principle, Bohr takes issue with Heisenberg's epistemic interpretation because he helps himself to the idea that there are independently existing objects with inherent properties to measure. Elsewhere Bohr suggests that the "mechanical conception of nature" is not consistent with quantum theory: "The recognition that the interaction between the measuring tools and the physical systems under investigation constitutes an unsuspected limitation of the mechanical conception of nature, as characterized by attribution of separate properties to physical systems, but has forced us, in the ordering of experience, to pay proper attention to the conditions of observation" (Bohr 1963b [1954 essay], 74). And he also explicitly states that the indeterminate nature of the measurement interaction entails "the necessity of a final renunciation of the classical ideal of causality and *a radical revision of our attitude towards the problem of physical reality*" (Bohr 1963b [1949 essay], 60; italics mine).

Bohr takes a positive stance on how he understands the nature of reality in a crucial response to Einstein. In 1935, Einstein and two colleagues, Boris Podolsky and Nathan Rosen, published a paper that specifically raises the question of how quantum mechanics would have us understand the nature of reality. In my effort to provide a consistent Bohrian meaning for the term "reality," I turn to a crucial passage from Bohr's response to the famous "EPR paper," in which Bohr specifically rejects the EPR definition of "physical reality."[45] Many scholars have pointed out that the argument Bohr articulates in this passage is pivotal to his attempt to discredit the analysis of Einstein and his colleagues and to resolve the EPR paradox once and for all. I say this both to highlight the fact that I have chosen not some obscure or arbitrary passage from Bohr's writings but the one in which Bohr has the most at stake in being careful with the presentation of his ideas on the notion of reality, and also to express my surprise that none of the scholarship that I have read on Bohr emphasizes the *positive* feature of this passage—that Bohr offers his own definition of physical reality in the final sentence:[46]

> From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky, and Rosen contains an ambiguity as regards the meaning of the expression "without in any way disturbing the system." Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.* Since these conditions constitute an inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete. (Bohr 1935, 700; italics in original)

In discussing Bohr's use of the word "phenomenon" earlier, I pointed out that the "conditions which define the possible types of predictions" constitute an inherent element of the description of any phenomenon. Therefore the first phrase of the last sentence is consistent with Bohr's use of the term "phenomenon."[47] The last sentence then indicates that *the term "physical reality" can properly be attached to phenomena*.

Let's take another look at Bohr's notion of phenomenon. First, recall that Bohr's analysis of measurement interactions shows that the indeterminable discontinuity undermines the classical belief in an inherent subject-object distinction. Indeed, he calls into question the very notion that objects have an independent existence separate from the conditions of determinability specified by the apparatus. Bohr's writings on complementarity focus on the inherent semantic indeterminacy and the profound epistemological implications of the lack of inherent separation between knower and known, but I propose that it is not a stretch to understand the indeterminacies to be at once semantic *and* ontic (not merely epistemic). Indeed, although Bohr does not make such an explicit claim, as I've indicated in my explication of his views, there is justifiable reason to do so (including, notably, his rejection of the metaphysical presupposition, embraced by Heisenberg, that objects have preexisting properties that are disturbed by the measurement process). Making the ontological nature of this indeterminacy explicit entails a rejection of the *classical metaphysical assumption that there are determinate objects with determinate properties and corresponding determinate concepts with determinate meanings independent of the necessary conditions needed to resolve the inherent indeterminacies.* The necessary condition for resolving the inherent ontic-semantic indeterminacy is the existence of a specific measurement apparatus. In other words, *the measurement apparatus is the condition of possibility for determinate meaning for the concept in question, as well as the condition of possibility for the existence of determinately bounded and propertied (sub)systems, one of which marks the other in the measurement of the property in question.* In particular, apparatuses provide the conditions for the possibility of determinate boundaries and properties of "objects" within phenomena, where "*phenomena*" *are the ontological inseparability of objects and apparatuses*.[48]

Since individually determinate entities do not exist, measurements do not entail an interaction between separate entities; rather, determinate entities emerge from their *intra-action*. I introduce the term "intra-action" in recognition of their ontological inseparability, in contrast to the usual "interaction," which relies on a metaphysics of individualism (in particular, the prior existence of separately determinate entities). A *phenomenon is a specific intra-action of an "object" and the "measuring agencies"*; the object and the measuring agencies emerge from, rather than precede, the intra-action that produces them.[49] Crucially, then, we should understand phenomena not as objects-in-themselves, or as perceived objects (in the Kantian or phenomenological sense), but as specific intra-actions. Because the basis of this ontology is a fundamental inseparability, it cuts across any Kantian noumena-phenomena distinction: there are no determinately bounded or propertied entities existing "behind" or as the causes of phenomena.[50] Not only is this ontological understanding of phenomena consistent with Bohr's insights; it is also consistent with recent experimental and theoretical developments in quantum physics (see chapter 7).

BOHR'S REALISM

Despite the vigorous challenges Bohr's account poses to representationalism, there is an important sense in which Bohr's account can be called "realist." The passage quoted in the previous section from Bohr's response to Einstein and his colleagues continues with the following remarks:

> On the contrary, this description, as appears from the preceding discussion, may be characterized as a rational utilization of all possibilities of unambiguous interpretation of measurements, compatible with the finite and uncontrollable interaction between objects and the measuring instruments in the field of quantum theory. In fact, it is only the mutual exclusion of any two experimental procedures, permitting the unambiguous definition of complementary physical quantities, which provides room for new physical laws, the co-existence of which might at first sight appear irreconcilable with the basic principles of science. It is just this entirely new situation as regards the description of physical phenomena that the notion of *complementarity* aims at characterizing. (Bohr 1935, 700; italics in original)

Notice that in this last sentence we are told that scientific theories describe physical phenomena. Were it not for the crucial ontological shift from observation-independent objects to physical phenomena, emphasizing the nonclassical nature of the Bohrian ontology, Bohr's statement would sound like the proclamation of a die-hard realist who is advocating a classical correspondence theory of truth. However, the "correspondence" in question is between theories and *phenomena*, not an observation-independent reality.[51]

Significantly, "correspondence" must symbolize something much richer and subtler philosophically than the usual denotation of this term, since, as I indicated earlier in the chapter, Bohr points to the failure of representationalism on which correspondence theories of truth are premised. Likewise, "description" cannot have the same valence it has in representationalist theories, since in Bohr's account theoretical concepts are not mere ideations but are materially embodied in apparatuses that produce the phenomena being described. That is, there's an important sense in which Bohr's framework offers a proto-performative account of the production of bodies. I offer a further elaboration of the performative dimensions of Bohr's account in the next chapter. Granting these important caveats, there is nonetheless something importantly realist about Bohr's formulation, as the sentence identifying a correspondence relation indicates. Furthermore, Bohr's commitment to finding a way to hang on to objectivity in the face of the significant role of "subjective elements" such as human concepts in the production of phenomena underlines his opposition to idealism and relativism. Apparatuses are not Kantian conceptual frameworks; they are physical arrangements. And phenomena do not refer merely to perception of the human mind; rather, phenomena are real physical entities or beings (though not fixed and separately delineated things). Hence I conclude that Bohr's framework is consistent with a particular notion of realism, which is not parasitic on subject-object, culture-nature, and word-world distinctions.

CAUSALITY

As Bohr points out, the inseparability of the object from the apparatus "entails . . . the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality" (Bohr 1963b [1949 essay], 59–60). While claiming that his analysis forces him to issue a final renunciation of the classical ideal of causality, that is, of strict determinism, Bohr does not presume that this entails overarching disorder, randomness, or an outright rejection of the cause-and-effect relationship. Rather, he suggests that our understanding of the terms of that relationship must be reworked: "The feeling of volition and the demand for causality are equally indispensable elements in the relation between subject and object which forms the core of the problem of knowledge" (Bohr 1963a [1929 essay], 117). In short, he rejects both poles of the usual dualist thinking about causality—absolute freedom and strict determinism:

> These problems were instructively commented upon from different sides at the Solvay meeting. . . . On that occasion an interesting discussion arose also about how to speak of the appearance of phenomena. . . . The question was whether, as to the occurrence of individual effects, we should adopt a terminology proposed by Dirac, that we were concerned with a choice on the part of "nature" or, as suggested by Heisenberg, we should say that we have to do with a choice on the part of the "observer" constructing the measuring instruments and reading their recording. Any such terminology would, however, appear dubious since, on the one hand, it is hardly reasonable to endow nature with volition in the ordinary sense, while, on the other hand, it is certainly not possible for the observer to influence the events which may appear under the conditions he [or she] has arranged. To my mind, there is no other alternative than to admit that, in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena we want to study. (Bohr 1963b [1949 essay], 223)[52]

That is, there must be a way of recognizing the nature of agency that transcends the assumed inherent or Cartesian subject-object distinction. Indeed, Bohr's term "agencies of observation" evokes his new understanding of the nature and role of agency in scientific practices, although this understanding is not developed in his writings. While I will save such theoretical developments for later chapters, at this point I want to highlight a few important features of the new sense of causality.

First of all, it is important to realize that this new sense of causality cannot be founded on a simple combination of classical options such as the following: there is, on the one hand, absolute freedom in our choice of apparatus, and, on the other, a strict deterministic causal relationship whereby objects simply "do their thing" once the apparatus has been chosen. This combination is neither as rich nor as subtle as what I believe Bohr had in mind, or should have had in mind, because each of these elements is premised on the contested inherent or Cartesian dualism. But

neither is this to suggest that human beings determine the outcome or play an "interventionist role," stepping forward, tweaking a few dials, and stepping back to watch, since these kinds of claims are also conditioned by the same contested dualisms. Second, causality is too often conceptualized as a binary affair: either a situation of strict determinism applies (i.e., causal determination) or there is a state of freedom (i.e., no causal determination). However, there are more ways to think about causal relations than the usual choices between determinism and free will (as Bohr specially mentions). Since traditional formulations of causality assume that independently determinate entities precede some causal interaction, we are clearly already on very new ground. Third, the fact that scientific results are reproducible requires (or at least seems to require) that intra-actions entail some kind of causal structure—that is, something being the cause, and something the effect—otherwise it would be impossible (or at least very difficult) to account for the reproducibility of experiments. Finally, it seems important to consider whether it even makes sense to attribute the notion of agency solely to human beings, since this particular conception already seems to be undone by the analyses we have been considering. Indeed, the issue is not merely who or even what gets to have agency or whether or not culture or nature determines a particular outcome, but also what the notion of intra-actions tells us about the nature of causality such that we will be able to account for how the distinctions between "nature" and "culture," "human" and "nonhuman," and "science" and "society" are produced, what that production entails, and how we are to understand the nature of agency.

FOUR

Agential Realism: How Material-Discursive Practices Matter

> Where did we ever get the strange idea that nature—as opposed to culture—is ahistorical and timeless? We are far too impressed by our own cleverness and self-consciousness. . . . We need to stop telling ourselves the same old anthropocentric bedtime stories.
>
> —STEVE SHAVIRO, *Doom Patrols*

Language has been granted too much power. The linguistic turn, the semiotic turn, the interpretative turn, the cultural turn: it seems that at every turn lately every "thing"—even materiality—is turned into a matter of language or some other form of cultural representation. The ubiquitous puns on "matter" do not, alas, mark a rethinking of the key concepts (materiality and signification) and the relationship between them. Rather, they seem to be symptomatic of the extent to which matters of "fact" (so to speak) have been replaced with matters of signification (no scare quotes here). Language matters. Discourse matters. Culture matters. There is an important sense in which the only thing that doesn't seem to matter anymore is matter.

TAKING MATTER SERIOUSLY: MATERIALITY AND PERFORMATIVITY

What compels the belief that we have a direct access to cultural representations and their content that we lack toward the things represented? How did language come to be more trustworthy than matter? Why are language and culture granted their own agency and historicity, while matter is figured as passive and immutable or at best inherits a potential for change derivatively from language and culture? How does one even go about inquiring after the material conditions that have led us to such a brute reversal of naturalist beliefs when materiality itself is always already figured within a linguistic domain as its condition of possibility?

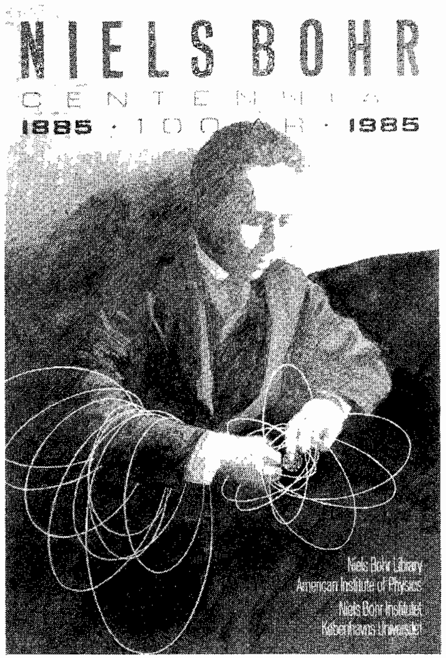
It is hard to deny that the power of language has been substantial. One might argue that it has been too substantial, or perhaps more to the point,

too substantializing. Neither an exaggerated faith in the power of language nor the expressed apprehension that language is being granted too much power is a novel feature of the late twentieth century and the early twenty-first. For example, during the nineteenth century, Nietzsche warned against the mistaken tendency to take grammar too seriously: allowing linguistic structure to shape or determine our understanding of the world, believing that the subject-and-predicate structure of language reflects a prior ontological reality of substance and attribute. The belief that grammatical categories reflect the underlying structure of the world is a continuing seductive habit of mind worth questioning.

Is it not, after all, the common-sense view of representationalism—the belief that representations serve a mediating function between knower and known—that displays a deep mistrust of matter, holding it off at a distance, figuring it as passive, immutable, and mute, in need of the mark of an external force like culture or history to complete it? Indeed, the representationalist belief in the power of words to mirror preexisting phenomena is the metaphysical substrate that supports social constructivist, as well as traditional realist, beliefs, perpetuating the endless recycling of untenable options. Significantly, social constructivism has been the object of intense scrutiny within both feminist and science studies circles where considerable and informed dissatisfaction has been voiced.[1]

A *performative* understanding of discursive practices challenges the representationalist belief in the power of words to represent preexisting things. Unlike representationalism, which positions us above or outside the world we allegedly merely reflect on, a performative account insists on understanding thinking, observing, and theorizing as practices of engagement with, and as part of, the world in which we have our being.

Performativity, properly construed, is not an invitation to turn everything (including material bodies) into words; on the contrary, performativity is precisely a contestation of the excessive power granted to language to determine what is real. Hence, in ironic contrast to the misconception that would equate performativity with a form of linguistic monism that takes language to be the stuff of reality, performativity is properly understood as a contestation of the unexamined habits of mind that grant language and other forms of representation more power in determining our ontologies than they deserve.[2]



13 This Niels Bohr centennial celebration poster depicts the scientist in his youth, absorbed in the task of constructing atoms. In his hands and along the length of his arm are discrete electron orbitals, the basis of his model of the atom, which applies quantum ideas to matter. Bohr won the Nobel Prize in 1922 for his model of the atom. *Reprinted with permission of the artist Liam Roberts, courtesy AIP Emilio Segrè Archives.*

HUMANIST ORBITS

Gazing out into the night sky or deep down into the structure of matter, with telescope or microscope in hand, Man reconfirms his ability to negotiate immense differences in scale in the blink of an eye. Designed specifically for our visual apparatus, telescopes and microscopes are the stuff of mirrors, reflecting what is out there. Nothing is too vast or too minute. Though a mere speck, a blip on the radar screen of all that is, Man is the center around which the world turns. Man is the sun, the nucleus, the fulcrum, the unifying force, the glue that holds it all together. Man is an individual apart from all the rest. And it is this very distinction that bestows on him the inheritance of distance, a place from which to reflect—on the world, his fellow man, and himself. A distinct individual, the unit of all measure, finitude made flesh, his separateness is the key.

Representationalism, metaphysical individualism, and humanism work hand in hand, holding this worldview in place. These forces have such a powerful grip on contemporary patterns of thought that even some of the most concerted efforts to escape the grasp of these anthropocentric forces have failed. Niels Bohr's philosophy-physics poses an energetic challenge

not only to Newtonian physics and metaphysics but to representationalism and concordant epistemologies, such as conventional forms of realism and social constructivism, as well. Poststructuralist theorists such as Michel Foucault and Judith Butler blast the tenets of humanism and representationalism in an attempt to harness the force of this explosion to garner sufficient momentum against the threshold escape velocity. Each of these powerful attempts rockets our cultural imaginary out of a well-worn stable orbit. But ultimately the power of these vigorous interventions is insufficient to fully extricate these theories from the seductive nucleus that binds them, and it becomes clear that each has once again been caught in some other orbit around the same nucleus. Suitably energetic to cause significant perturbations, nonetheless, the prized ionization is thwarted in each case by anthropocentric remainders. What is needed is a rigorous simultaneous challenge to all components of this gripping long-range force.[3]

In this chapter, I propose a *posthumanist performative* approach to understanding technoscientific and other naturalcultural practices that specifically acknowledges and takes account of matter's dynamism.[4] The move toward performative alternatives to representationalism shifts the focus from questions of correspondence between descriptions and reality (e.g., do they mirror nature or culture?) to matters of practices, doings, and actions. Such an approach also brings to the forefront important questions of ontology, materiality, and agency, while social constructivist and traditional realist approaches get caught up in the geometrical optics of reflection where, much like the infinite play of images between two facing mirrors, the epistemological gets bounced back and forth, but nothing more is seen. Moving away from the representationalist trap of geometrical optics, I shift the focus to physical optics, to questions of diffraction rather than reflection.[5] Diffractively reading the insights of poststructuralist theory, science studies, and physics through one another entails thinking the cultural and the natural together in illuminating ways. What often appears as separate entities (and separate sets of concerns) with sharp edges does not actually entail a relation of absolute exteriority at all. Like the diffraction patterns illuminating the indefinite nature of boundaries—displaying shadows in "light" regions and bright spots in "dark" regions—the relationship of the cultural and the natural is a relation of "exteriority within." This is not a static relationality but a doing—the enactment of boundaries—that always entails constitutive exclusions and therefore requisite questions of accountability. One of my aims is to contribute to efforts to sharpen the theoretical tool of performativity for science studies and feminist theory endeavors alike, and to promote their mutual consideration. Crucially, an agential realist elaboration of performativity allows matter its due as an active participant in the world's becoming, in its ongoing intra-activity. And furthermore it provides an understanding of *how* discursive practices matter.

Refusing the anthropocentrisms of humanism and antihumanism, *posthumanism* marks the practice of accounting for the boundary-making practices by which the "human" and its others are differentially delineated and defined.[6] In invoking this contested term, I want to be clear that I am not interested in postmodernist celebrations (or demonizations) of the posthuman as living testimonies to the death of the human, nor as the next stage of Man. No uncritical embrace of the cyborg as the ironic liberatory savior is at issue here.[7] Posthumanism, as I intend it here, is not calibrated to the human; on the contrary, it is about taking issue with human exceptionalism while being accountable for the role we play in the differential constitution and differential positioning of the human among other creatures (both living and nonliving). Posthumanism does not attribute the source of all change to culture, denying nature any sense of agency or historicity. In fact, it refuses the idea of a natural (or, for that matter, a purely cultural) division between nature and culture, calling for an accounting of how this boundary is actively configured and reconfigured. Posthumanism does not presume that man is the measure of all things. It is not held captive to the distance scale of the human but rather is attentive to the practices by which scale is produced. Posthumanism has no patience for principled claims presuming the banishment or death of metaphysics, especially when such haughty assertions turn out to be decoys for the covert resurrection of Man as the unspoken measure of what is and isn't observable or intelligible.[8] It doesn't abide by prohibitions against talk of ontology, restricting all deliberation to the epistemological (moored at the safe harbor of Man). Posthumanism eschews both humanist and structuralist accounts of the subject that position the human as either pure cause or pure effect, and the body as the natural and fixed dividing line between interiority and exteriority. Posthumanism doesn't presume the separateness of any-"thing," let alone the alleged spatial, ontological, and epistemological distinction that sets humans apart.

In fact, the agential realist ontology that I propose does not take separateness to be an inherent feature of how the world is. But neither does it denigrate separateness as mere illusion, an artifact of human consciousness led astray. Difference cannot be taken for granted; it matters—indeed, it *is* what matters. The world is not populated with things that are more or less the same or different from one another. Relations do not follow relata, but the other way around. Matter is neither fixed and given nor the mere end result of different processes. Matter is produced and productive, generated and generative. Matter is agentive, not a fixed essence or property of things. Mattering is differentiating, and which differences come to matter, matter in the iterative production of different differences. Changing patterns of difference are neither pure cause nor pure effect; indeed, they are that which effects, or rather enacts, a causal structure, differentiating cause and effect. Difference patterns do not merely change in time and space; spacetime is an enactment of differentness, a way of making/marking here and now.

AN AGENTIAL REALIST ONTOLOGY

Reality is bigger than us.

—IAN HACKING, *Representing and Intervening*

I think the world is precisely what gets lost in doctrines of representation and scientific objectivity.

—DONNA HARAWAY, "The Promises of Monsters"

Representationalism takes the notion of separation as foundational. It separates the world into the ontologically disjunct domains of words and things, leaving itself with the dilemma of their linkage such that knowledge is possible. If words are untethered from the material world, how do representations gain a foothold? If we no longer believe that the world is teeming with inherent resemblances whose signatures are inscribed on the face of the world, things already emblazoned with signs, words lying in wait like so many pebbles of sand on a beach there to be discovered, but rather that the knowing subject is enmeshed in a thick web of representations such that the mind cannot see its way to objects that are now forever out of reach and all that is visible is the sticky problem of humanity's own captivity within language, then it becomes apparent that representationalism is a prisoner of the problematic metaphysics it postulates. Like the frustrated would-be runner in Zeno's paradox, representationalism never seems to get any closer to solving the problem it poses because it is caught in the impossibility of stepping outward from its metaphysical starting place. What is needed is a new starting place.

The postulation of individually determinate entities with inherent properties is the hallmark of atomistic metaphysics. Atomism hails from Democritus.[9] According to Democritus, the properties of all things derive from the properties of the smallest unit—atoms (the "uncuttable" or "inseparable"). Liberal social theories and scientific theories alike owe much to the idea that the world is composed of individuals with separately attributable properties. An entangled web of scientific, social, ethical, and political practices, and our understanding of them, hinges on the various differential instantiations of this presupposition. Much hangs in the balance in contesting its seeming inevitability.

Niels Bohr won the Nobel Prize for his quantum model of the atom, which marks the beginning of his seminal contributions to the development of the quantum theory. Crucially, however, in a stunning reversal of his intellectual forefather's schema, Bohr rejects the atomistic metaphysics that takes "things" as ontologically basic entities. For Bohr, things do not have inherently determinate boundaries or properties, and words do not have inherently determinate meanings. Bohr also calls into question the related Cartesian belief in the inherent distinction between subject and object, and knower and known. Indeed, Bohr's philosophy-physics poses a radical challenge not only to Newtonian physics but also to Cartesian epistemology and its representationalist triadic structure of words, knowers, and things.[10]

It might be said that the epistemological framework that Bohr develops rejects both the transparency of language and the transparency of measurement; however, even more fundamentally, it rejects the presupposition that language and measurement perform mediating functions. Language does not represent states of affairs, and measurements do not represent measurement-independent states of being. Bohr develops his epistemological framework without giving in to the despair of nihilism or the dizziness of relativism. With brilliance and finesse, Bohr finds a way to hold on to the possibility of objective knowledge as the grand structures of Newtonian physics and representationalism begin to crumble.

Bohr's break with Newton, Descartes, and Democritus is based not in "mere idle philosophical reflection" but on new empirical findings in the domain of atomic physics that came to light during the first quarter of the twentieth century. Bohr's struggle to provide a theoretical understanding of these findings resulted in his radical proposal that an entirely new epistemological framework is required. Unfortunately Bohr does not explore the crucial ontological dimensions of his insights but rather focuses on their epistemological import. I have mined his writings for his implicit ontological views (see chapter 3) and here elaborate on them in the development of an agential realist ontology.

In this section, I present a brief overview of important aspects of Bohr's account and move on to an explication of an agential realist ontology. This relational ontology is the basis for my posthumanist performative account of material bodies (both human and nonhuman). This account refuses the representationalist fixation on words and things and the problematic of the nature of their relationship, advocating instead *a relationality between specific material (re)configurings of the world through which boundaries, properties, and meanings are differentially enacted* (i.e., discursive practices, in my posthumanist sense) *and specific material phenomena* (i.e., differentiating patterns of mattering).[11] This causal relationship between the apparatuses of bodily production and the phenomena produced is one of agential intra-action.[12] The details follow.

According to Bohr, *theoretical concepts* (e.g., position and momentum) are not ideational in character but rather *specific physical arrangements*.[13] For example, the notion of position cannot be presumed to be a well-defined abstract concept; nor can it be presumed to be an individually determinate attribute of independently existing objects. Rather, position has meaning only when an apparatus with an appropriate set of fixed parts is used. And furthermore, any measurement of position using this apparatus cannot be attributed to some abstract, independently existing object but rather is a property of the *phenomenon*—the inseparability of the object and the measuring agencies. Similarly, momentum is meaningful only as a material arrangement involving a specific set of movable parts. Hence the indeterminacy of simultaneous position and momentum measurements is a straightforward matter of the material exclusion of position and momentum arrangements (one requiring fixed parts, and the complementary arrangement requiring those same parts to be movable).

As I argued in chapter 3, the primary ontological unit is not independent objects with inherent boundaries and properties but rather *phenomena*. In my agential realist elaboration, phenomena do not merely mark the epistemological inseparability of observer and observed, or the results of measurements; rather, *phenomena are the ontological inseparability/entanglement of intra-acting "agencies."* That is, phenomena are ontologically primitive relations—relations without preexisting relata.[14] The notion of *intra-action* (in contrast to the usual "interaction," which presumes the prior existence of independent entities or relata) represents a profound conceptual shift. It is through specific agential intra-actions that the boundaries and properties of the components of phenomena become determinate and that particular concepts (that is, particular material articulations of the world) become meaningful. Intra-actions include the larger material arrangement (i.e., set of material practices) that effects an *agential cut* between "subject" and "object" (in contrast to the more familiar Cartesian cut which takes this distinction for granted). That is, the agential cut enacts a resolution *within* the phenomenon of the inherent ontological (and semantic) indeterminacy. In other words, relata do not preexist relations; rather, relata-within-phenomena emerge through specific intra-actions. Crucially, then, intra-actions enact *agential separability*—the condition of *exteriority-within-phenomena*. The notion of agential separability is of fundamental importance, for in the absence of a classical ontological condition of exteriority between observer and observed, it provides an alternative ontological condition for the possibility of objectivity. Moreover, the agential cut enacts a causal structure among components of a phenomenon in the marking of the "measuring agencies" ("effect") by the "measured object" ("cause"). It is in this sense that the measurement can be said to express particular facts about that which is measured; that is, the measurement is a causal intra-action and not "any old playing around."[15] Hence *the notion of intra-action constitutes a reworking of the traditional notion of causality*.[16]

In my further elaboration of this agential realist ontology, I argue that phenomena are not the mere result of laboratory exercises engineered by human subjects; rather, *phenomena are differential patterns of mattering* ("diffraction patterns") produced through complex agential intra-actions of multiple material-discursive practices or apparatuses of bodily production, where *apparatuses are not mere observing instruments but boundary-drawing practices—specific material (re)configurings of the world—which come to matter*. These causal intra-actions need not involve humans. Indeed, it is through such practices that the differential boundaries between humans and nonhumans, culture and nature, science and the social, are constituted.[17]

Phenomena are constitutive of reality. Reality is composed not of things-in-themselves or things-behind-phenomena but of things-in-phenomena.[18] The world is a dynamic process of intra-activity and materialization in the enactment of determinate causal structures with determinate boundaries, properties, meanings, and patterns of marks on bodies. This ongoing flow of agency through which part of the world makes itself differentially intelligible to another part of the world and through which causal structures are stabilized and destabilized does not take place in space and time but happens in the making of spacetime itself. It is through specific agential intra-actions that a differential sense of being is enacted in the ongoing ebb and flow of agency.[19] That is, it is through specific intra-actions that phenomena come to matter—in both senses of the word.

The world is an open process of mattering through which mattering itself acquires meaning and form through the realization of different agential possibilities. Temporality and spatiality emerge in this processual historicity. Relations of exteriority, connectivity, and exclusion are reconfigured. The changing topologies of the world entail an ongoing reworking of the notion of dynamics itself. Dynamics are a matter not merely of properties changing in time but of what matters in the ongoing materializing of different spacetime topologies. The world is intra-activity in its differential mattering.

In summary, the primary ontological units are not "things" but phenomena—dynamic topological reconfigurings/entanglements/relationalities/(re)articulations of the world. And the primary semantic units are not "words" but material-discursive practices through which (ontic and semantic) boundaries are constituted. This dynamism is agency. Agency is not an attribute but the ongoing reconfigurings of the world. The universe is agential intra-activity in its becoming.

In what follows, I provide a detailed explication of this agential realist ontology. I begin with a detailed examination of the nature of the apparatus, including two significant analytical shifts that are important emendations to Bohr's formulation: (1) a shift from linguistic representations to discursive practices; and (2) a shift from apparatuses as static prefab laboratory setups to an understanding of apparatuses as material-discursive practices through which the very distinction between the social and the scientific, nature and culture, is constituted.

THE NATURE OF AN APPARATUS

> The opportunity to know the apparatus better. . . . That is an integral part of knowing how to create phenomena.
>
> IAN HACKING, *Representing and Intervening*

What is an apparatus? Is it the set of instruments needed to perform an experiment? Is it a meditating device that allows the object world to give us a sign of its nature? Is it a prosthetic extension of our sensing abilities? Shall we understand an apparatus in terms of Kantian grids of intelligibility? Aristotelian schemata? Heideggerian background practices? Althusserian apparatuses? In Foucault's sense of discursive practices or *dispositif* (apparatus)? In Butler's sense of the performative? As Latour's inscription or translation devices? Or as Haraway's apparatuses of bodily production? Bohr's notion of an apparatus is unique among these theorizations, and yet there are some interesting reverberations among these possibilities worth exploring. Reverberating at different frequencies, these differing lines of thought can productively be read through one another for the patterns of resonance and dissonance that illuminate new possibilities for understanding and for being.

Since apparatuses play such a crucial, indeed constitutive, role, it is imperative that we understand their precise nature. In this chapter I argue that apparatuses are not mere instruments or devices that can be deployed as neutral probes of the natural world, or determining structures of a social nature, but neither are they merely laboratory instruments or social forces that function in a performative mode. Apparatuses are not merely about us. And they are not merely assemblages that include nonhumans as well as humans. Rather, apparatuses are specific material reconfigurings of the world that do not merely emerge in time but iteratively reconfigure spacetimematter as part of the ongoing dynamism of becoming.

THE BOUNDARY OF AN APPARATUS

Bohr specifies certain specific criteria for apparatuses. According to Bohr, apparatuses are macroscopic material arrangements through which particular concepts are given definition, to the exclusion of others, and through which particular phenomena with particular determinate physical properties are produced. The far-reaching conclusion of Bohr's proto-performative analysis is that the apparatus plays a much more active and intimate role in experimental practices than classical physics recognizes. Apparatuses are not passive observing instruments; on the contrary, they are productive of (and part of) phenomena. Yet despite the centrality of the apparatus to Bohr's analysis, he never fully articulates its nature.

Questioning the basis of the Newtonian tradition, Bohr refuses to take for granted the delineation of the "object" and the "agencies of observation" and makes the constitution of this "inside" boundary the centerpiece of his analysis. In particular, he emphasizes that the cut delineating the object from the agencies of observation is enacted rather than inherent. On the other hand, Bohr does seem to help himself to the "outside" boundary of the apparatus. That is, while focusing on the lack of an inherent distinction between measuring instrument and measured object, Bohr does not directly address the question of where the apparatus "ends." Is the outside boundary of the apparatus coincident with the visual terminus of the instrumentation? What if an infrared interface (i.e., a wireless connection) exists between the measuring instrument and a computer that collects the data? Does the apparatus include the computer? Is the printer attached to the computer part of the apparatus? Is the paper that is fed into the printer? Is the person who feeds in the paper? How about the person who reads the marks on the paper? Or the scientists and technicians who design, build, and run the experiment? How about the community of scientists who judge the significance of the experiment and indicate their support or lack of support for future funding? What precisely constitutes the limits of the apparatus that gives meaning to certain concepts at the exclusion of others?

One of the questions, perhaps *the* question, that Bohr finds most pressing in his investigation of measurement practices is how it is possible to secure the conditions for the possibility of objectivity given that "subjective elements" such as human concepts play a productive (though not determining) role in the outcome of measurements. In other words, what is at stake for him in the challenge posed by quantum physics is nothing less than how we can account for the fact that science works. Crucial to Bohr's analysis of the subject-object distinction is his insistence that concepts are materially embodied in the apparatus. In particular, Bohr insists that only concepts defined by their specific embodiment as part of the material arrangement—which includes instrumentation (e.g., photographic plates, pointers, or digital readout devices) that marks definite values of the specifically defined properties and can be read by a human observer—are meaningful. That is, the larger material arrangement enacts a cut that resolves the inherent ontic-semantic indeterminacy through which the "subject" and the "object" emerge. Apparatuses are the conditions of possibility for determinate boundaries and properties of objects and meanings of embodied concepts within the phenomenon. Indeed, this embodiment of concepts as part of the apparatus is ultimately what secures the possibility of objective knowledge, as defined in terms of Bohr's epistemic criteria of reproducibility and communicability.[20] One pronounced limitation of Bohr's account, then, is that the human is thereby cemented into the very foundations of the quantum theory and the far-reaching philosophical implications of his proto-performative account of scientific practices. Observation and communication, the contingencies of visibility and invisibility, of concepts and utterances, are crucial to this formulation: man isn't merely the measure of all things; man's finitude is implicated in the very conditions of possibility of measurability and determinability. It is as if in the desire to compensate for the shortcomings of classical mechanics—which erroneously jettisons the observer from the scene of observation—Bohr overshoots his mark and places the human not merely back in the picture where she or he belongs, but at the center of all that is.

Furthermore, Bohr's conception of the apparatus does not accurately take account of the complexities of experimental practice, despite his apparent intentions to do just that. Quite atypical of the writings of theoretical physicists, Bohr's papers include detailed drawings of measuring instruments. His attentiveness to the details of the apparatus makes perfect sense given his insistence that the concepts used to describe phenomena are not ideations but specific material arrangements: for Bohr, word and world are tied to each other. Nonetheless Bohr treats the apparatus itself as an ideal measuring device that springs full blown from the head of Zeus, operates itself or at most requires the pushing of a few buttons to produce results, requires no tinkering, no maintenance, no muss, no fuss. Its constitutionality remains constant—no rearrangements, no alterations, no adjustments. It is frozen at a moment in time, denied its historicity and mutability. In an important sense, then, Bohr's apparatus is hermetically sealed off from any and all "outside" influences. The scientist is a liberal humanist subject who is merely there to choose an appropriate apparatus for the investigation and note the results. Once the apparatus is in place, the scientist stands back and watches what happens.

In short, Bohr mistakes the apparatus for a mere laboratory setup. Magically, the scientific instrumentation works correctly without intervention, reducing the role of the experimenter to a mere recorder of the objective marks displayed by the instrumentation.[21] For all of Bohr's insistence on thinking realistically about apparatuses, refusing to contemplate them as idealized forms, he artificially cuts "the apparatus" off from all the activities that enable experimental practice to work. As Hacking notes:

> Most experiments don't work most of the time. To ignore this fact is to forget what experimentation is doing.
>
> To experiment is to create, produce, refine and stabilize phenomena. . . . But phenomena are hard to produce in any stable way. That is why I spoke of creating and not merely discovering phenomena. That is a long hard task.
>
> Or rather there are endless different tasks. There is designing an experiment that might work. There is learning how to make the experiment work. But perhaps the real knack is getting to know when the experiment is working. That is one reason why observation, in the philosophy-of-science usage of the term, plays a relatively small role in experimental science. Noting and reporting readings of dials—Oxford philosophy's picture of experiment—is nothing. Another kind of observation is what counts: the uncanny ability to pick out what is odd, wrong, instructive or distorted in the antics of one's equipment. The experimenter is not the "observer" of traditional philosophy of science, but rather the alert and observant person. Only when one has got the equipment running right is one in a position to make and record observations. That is a picnic. (1983, 230)

Bohr's figuration of the apparatus makes it inoperable in practice.[22]

The liberal humanist conception of the subject and the taken-for-granted static and bounded apparatus that are embodied in Bohr's theoretical apparatus get in the way of his efforts to provide a deeper understanding of the nature of scientific practices and ultimately cut short the profound ontological implications of his ideas. In taking for granted an intrinsic outside boundary of the apparatus, which incorporates human concepts within its bounds while ejecting the observer to the outside, Bohr reifies the selfsame "subjective elements" he sets out to tame, ignoring the dynamism of discursive practices and the co-constitution of subjects along with objects. Bohr seems to have forgotten his own lesson that cuts are part of the phenomena they help produce. What is needed is a posthumanist understanding of the role of the apparatus and of the human and the relationship between them.

TOWARD AN AGENTIAL REALIST UNDERSTANDING OF APPARATUSES

One task that stands before us is to further elaborate Bohr's immensely important insights while removing the less savory anthropocentric elements, including his dependence on the notion of human concepts and laboratory setups. As we have seen, it is also important to take into account the dynamic and complex nature of scientific practices. In recent years, critical social theorists have offered sophisticated accounts of the practices by which meanings, boundaries, and bodies are produced. The problem is that these accounts are invested and enmeshed in a host of anthropocentric assumptions as well. For example, Judith Butler's performative account of mattering thinks the matter of materiality and signification together in their indissolubility; however, Butler's concern is limited to the production of human bodies (and only certain aspects of their production, at that), and her theorization of materialization is parasitic on Foucault's notions of regulatory power and discursive practices, which are limited to the domain of human social practices. Furthermore, for both Butler and Foucault, agency belongs only to the human domain, and neither addresses the nature of technoscientific practices and their profoundly productive effects on human bodies, as well as the ways in which these practices are deeply implicated in what constitutes the human, and more generally the workings of power. That is, both accounts honor the nature-culture binary (to different degrees), thereby deferring a thoroughgoing genealogy of its production.[23] Crucially, Butler's and Foucault's theories fail to provide an adequate account of the relationship between discursive practices and material phenomena, leading one to wonder if Bohr's insights into the embodied nature of concepts might fruitfully intervene in this regard. What is needed is a posthumanist performative account of the material-discursive practices of mattering (including those that get labeled "scientific" and those that get labeled "social").

In what follows, I diffractively read the insights of Bohr, Foucault, Butler, and other important theorists through one another in an effort to advance such an account. This will entail important reworkings of the notions of materiality, discursive practices, agency, and causality, among others. My agential realist elaboration of apparatuses entails the following significant developments beyond Bohr's formulation: (1) apparatuses are specific material-discursive practices (they are not merely laboratory setups that embody human concepts and take measurements); (2) apparatuses produce differences that matter—they are boundary-making practices that are formative of matter and meaning, productive of, and part of, the phenomena produced; (3) apparatuses are material configurations/dynamic reconfigurings of the world; (4) apparatuses are themselves phenomena (constituted and dynamically reconstituted as part of the ongoing intra-activity of the world); (5) apparatuses have no intrinsic boundaries but are open-ended practices; and (6) apparatuses are not located in the world but are material configurations or reconfigurings of the world that re(con)figure spatiality and temporality as well as (the traditional notion of) dynamics (i.e., they do not exist as static structures, nor do they merely unfold or evolve in space and time).

MATTERING: A POSTHUMANIST PERFORMATIVE ACCOUNT OF MATERIAL-DISCURSIVE PRACTICES

Discourse is not a synonym for language.[24] Discourse does not refer to linguistic or signifying systems, grammars, speech acts, or conversations. To think of discourse as mere spoken or written words forming descriptive statements is to enact the mistake of representationalist thinking. Discourse is not what is said; it is that which constrains and enables what can be said. Discursive practices define what counts as meaningful statements. Statements are not the mere utterances of the originating consciousness of a unified subject; rather, statements and subjects emerge from a field of possibilities. This field of possibilities is not static or singular but rather is a dynamic and contingent multiplicity.

According to Foucault, discursive practices are the local sociohistorical material conditions that enable and constrain disciplinary knowledge practices such as speaking, writing, thinking, calculating, measuring, filtering, and concentrating. Discursive practices produce, rather than merely describe, the subjects and objects of knowledge practices. In Foucault's account, these conditions are immanent and historical rather than transcendental or phenomenological. That is, they are not conditions in the sense of ahistorical, universal, abstract laws defining the possibilities of experience (Kant), but actual historically and culturally specific social conditions.

Foucault's account of discursive practices has some provocative resonances (and some fruitful dissonances) with Bohr's account of apparatuses and the role they play in the material production of bodies and meanings. For Bohr, apparatuses are particular physical arrangements that give meaning to certain concepts to the exclusion of others; they are the local physical conditions that enable and constrain knowledge practices such as conceptualizing and measuring; they are productive of (and part of) the phenomena produced; they enact a local cut that produces "objects" of particular knowledge practices within the particular phenomena produced. On the basis of his profound insight that "concepts" (which are actual physical arrangements) and "things" do not have determinate boundaries, properties, or meanings apart from their mutual intra-actions, Bohr offers a new epistemological framework that calls into question the dualisms of object-subject, knower-known, nature-culture, and word-world.

Bohr's insight that concepts are not ideational but rather actual physical arrangements is clearly an insistence on the materiality of meaning making that goes beyond what is usually meant by the frequently heard contemporary refrain that writing and talking are material practices. Nor is Bohr merely claiming that discourse is "supported" or "sustained" by material practices, as Foucault seems to suggest (though the nature of this support is not specified), or that nondiscursive (background) practices determine discursive practices, as some existential-pragmatic philosophers purport.[25] Rather, Bohr's point entails a much more intimate relationship between concepts and materiality, matter and meaning.

The shift from linguistic concepts to discursive practices provides the possibility of freeing Bohr's account from its reliance on human concepts and the static nature of apparatuses in one move. At the same time, however, the notion of discursive practices must be appropriately reconceptualized to take account of their intrinsically material nature (and Bohr's insights are helpful here). The basic idea is to understand that it is not merely the case that human concepts are embodied in apparatuses, but rather that apparatuses *are* discursive practices, where the latter are understood as specific material reconfigurings through which "objects" and "subjects" are produced. I will offer such an elaboration in what follows. This shift will include a proposed posthumanist understanding of discursive practices and the role of the human, as well as some other important considerations. The agential realist ontology provides a basis for the necessary elaborations.

In my agential realist elaboration of Bohr's account, *apparatuses are the material conditions of possibility and impossibility of mattering*; they enact what matters and what is excluded from mattering. Apparatuses enact agential cuts that produce determinate boundaries and properties of "entities" within phenomena, where "phenomena" are the ontological inseparability of agentially intra-acting components. That is, agential cuts are at once ontic and semantic. It is only through specific agential intra-actions that the boundaries and properties of "components" of phenomena become determinate and that particular articulations become meaningful. In the absence of specific agential intra-actions, these ontic-semantic boundaries are indeterminate. In short, the apparatus specifies an agential cut that enacts a resolution (within the phenomenon) of the semantic, as well as ontic, indeterminacy. *Hence apparatuses are boundary-making practices.*

Now, as Bohr and Foucault would no doubt agree, meaning should not be understood as a property of individual words or groups of words. Meaning is neither intralinguistically conferred nor simply extralinguistically referenced. Meaning is made possible through specific material practices. Semantic contentfulness is achieved not through the thoughts or performances of individual agents but through particular discursive practices. However, the common belief that discursive practices and meanings are peculiarly human phenomena won't do. If discursive practices are boundary-making practices in an ontic (as well as semantic) sense, then the practices by which the human and the nonhuman are differentially constituted cannot rely on a notion of discursive practices that helps itself to a prior notion of the human. What is needed, then, is a posthumanist understanding of discursive practices.

In an agential realist account, *discursive practices are specific material (re)configurings of the world through which the determination of boundaries, properties, and meanings is differentially enacted.*[26] That is, *discursive practices are ongoing agential intra-actions of the world* through which specific determinacies (along with complementary indeterminacies) are enacted within the phenomena produced. Importantly, *discursive practices are causal intra-actions*—they enact causal structures through which some components (the "effects") of the phenomenon are marked by other components (the "causes") in their differential articulation. Meaning is not a property of individual words or groups of words but an ongoing performance of the world in its differential dance of intelligibility and unintelligibility. In its causal intra-activity, part of the world becomes determinately bounded and propertied in its emergent intelligibility to another part of the world, while lively matterings, possibilities, and impossibilities are reconfigured. Discursive practices are boundary-making practices that have no finality in the ongoing dynamics of agential intra-activity.

In traditional humanist accounts, intelligibility requires an intellective agent (that to which something is intelligible), and intellection is framed as a specifically human capacity. But in my agential realist account, intelligibility is an ontological performance of the world in its ongoing articulation. It is not a human-dependent characteristic but a feature of the world in its differential becoming. The world articulates itself differently.

Furthermore, knowing does not require intellection in the humanist sense, either. Rather, knowing is a matter of differential responsiveness (as performatively articulated and accountable) to what matters. As such, agential realism goes beyond both humanist and antihumanist accounts of the knowing subject as well as recent insights concerning the knower as a prosthetically enhanced human. Knowing is not about seeing from above or outside or even seeing from a prosthetically enhanced human body. Knowing is a matter of intra-acting. Knowing entails specific practices through which the world is differentially articulated and accounted for. In some instances, "nonhumans" (even beings without brains) emerge as partaking in the world's active engagement in practices of knowing.[27] Knowing entails differential responsiveness and accountability as part of a network of performances. Knowing is not a bounded or closed practice but an ongoing performance of the world.

Discursive practices are not speech acts, linguistic representations, or even linguistic performances, bearing some unspecified relationship to material practices. Discursive practices are not anthropomorphic placeholders for the projected agency of individual subjects, culture, or language. Indeed, they are not human-based practices. On the contrary, agential realism's posthumanist account of discursive practices does not fix the boundary between human and nonhuman before the analysis ever gets off the ground, but rather allows for the possibility of a genealogical analysis of the material-discursive emergence of the human. Human bodies and human subjects do not preexist as such; nor are they mere end products. Humans are neither pure cause nor pure effect but part of the world in its open-ended becoming.

Just as there are no words with determinate meanings lying in wait as so many candidates for an appropriate representational moment, neither are there things with determinate boundaries and properties whirling aimlessly in the void, bereft of agency, historicity, or meaning, which are only to be bestowed from the outside, as when the agency of Man pronounces the name that attaches to specific beings in the making of word-thing pairs. "Things" don't preexist; they are agentially enacted and become determinately bounded and propertied within phenomena. Outside of particular agential intra-actions, "words" and "things" are indeterminate. Matter is therefore not to be understood as a property of things but, like discursive practices, must be understood in more dynamic and productive terms—in terms of intra-activity.

In *Bodies That Matter*, Judith Butler gives a thorough accounting of the failures of social constructivist accounts of the body that circulate in feminist theory and challenges feminists to return to the notion of matter. But by this "return" she does not advocate reclaiming the precritical view that would position matter as that which is prior to discourse. She argues that any such attempt to ground feminist claims about sexual difference in such a prediscursive substance is doomed to beach itself on that very shore: matter, she explains, is already "fully sedimented with discourses on sex and sexuality that prefigure and constrain the uses to which that term can be put" (Butler 1993, 29). Instead Butler proposes that we understand matter as a "process of materialization that stabilizes over time to produce the effect of boundary, fixity, and surface we call matter" (9). She explains that her claim that "matter is always materialized has . . . to be thought in relation to the productive and, indeed, materializing effects of regulatory practices in the Foucaultian sense" (9–10).[28]

Butler's reconceptualization of matter as a process of materialization brings to the fore the importance of recognizing matter in its historicity and directly challenges representationalism's construal of matter as a passive and blank slate awaiting the active inscription of culture whereby the relationship between materiality and discourse is figured as one of absolute exteriority. Butler's account emphasizes the following important points. Matter, like meaning, is not an individually articulated or static entity. It is not little bits of nature, or a blank slate, surface, or site passively awaiting signification; nor is it an uncontested ground for scientific, feminist, or economic theories. Matter is not immutable or passive. Nor is it a fixed support, location, referent, or source of sustainability for discourse. It does not require the mark of an external force like culture or history to complete it. Matter is always already an ongoing historicity.

Unfortunately, however, Butler's theory ultimately reinscribes matter as a passive product of discursive practices rather than as an active agent participating in the very process of materialization.[29] This deficiency is symptomatic of an incomplete assessment of the causal factors of materialization and an incomplete reworking of "causality" in understanding the nature of discursive practices (and material phenomena) in their productivity. Furthermore, Butler's theory of materiality is limited to an account of the materialization of human bodies or, more accurately, to the construction of the contours of the human body. Moreover, as her reading of materiality in terms of Foucauldian regulatory practices makes clear, the processes that matter for her are only human social practices (thereby reinscribing the very nature-culture dichotomy she wishes to contest). Agential realism provides an understanding of materialization that goes beyond the anthropocentric limitations of Butler's theory. Significantly, it recognizes matter's dynamism.

In an agential realist account, matter does not refer to a fixed substance; rather, *matter is substance in its intra-active becoming—not a thing but a doing, a congealing of agency. Matter is a stabilizing and destabilizing process of iterative intra-activity.* Phenomena—the smallest material units (relational "atoms")—come to matter through this process of ongoing intra-activity. "Matter" does not refer to an inherent, fixed property of abstract, independently existing objects; rather, *"matter" refers to phenomena in their ongoing materialization.*

Matter is not simply "a kind of citationality" (Butler 1993, 15), the surface effect of human bodies, or the end product of linguistic or discursive acts. Matter is not a linguistic construction but a discursive production in the posthumanist sense that discursive practices are themselves material (re)configurings of the world through which the determination of boundaries, properties, and meanings is differentially enacted. That is, discursive practices as boundary-making practices are fully implicated in the dynamics of intra-activity through which phenomena come to matter. The dynamics of intra-activity entail matter as an active "agent" in its ongoing materialization. Or rather, *matter is a dynamic intra-active becoming that is implicated and enfolded in its iterative becoming. Matter(ing) is a dynamic articulation/configuration of the world.* In other words, materiality is discursive (i.e., material phenomena are inseparable from the apparatuses of bodily production; matter emerges out of, and includes as part of its being, the ongoing reconfiguring of boundaries), just as discursive practices are always already material (i.e., they are ongoing material [re]configurings of the world). Discursive practices and material phenomena do not stand in a relationship of externality to each other; rather, *the material and the discursive are mutually implicated in the dynamics of intra-activity*. The relationship between the material and the discursive is one of mutual entailment. Neither discursive practices nor material phenomena are ontologically or epistemologically prior. Neither can be explained in terms of the other. Neither is reducible to the other. Neither has privileged status in determining the other. Neither is articulated or articulable in the absence of the other; matter and meaning are mutually articulated.

Material constraints and exclusions and matter's historiality and agency (including, for example, the material dimensions of regulatory practices) are important factors in the process of materialization.[30] Material conditions matter, not because they "support" particular discourses that are the actual generative factors in the formation of bodies, but because *matter comes to matter* through the iterative intra-activity of the world in its becoming. The point is not merely that there are important material factors in addition to discursive ones; rather, the issue is the conjoined material-discursive nature of constraints, conditions, and practices. The fact that material and discursive constraints and exclusions are intertwined points to the limited validity of analyses that attempt to determine individual effects of material or discursive factors.[31]

Agential realism's conceptualization of materiality makes it possible to take account of material constraints and conditions once again without reinscribing traditional empiricist assumptions concerning the transparent or immediate givenness of the world and without falling into the analytical stalemate that simply calls for recognition of our mediated access to the world and then rests its case. The ubiquitous pronouncements that experience or the material world is "mediated" have offered precious little guidance about how to proceed. The notion of mediation has for too long stood in the way of a more thoroughgoing accounting of the empirical world. The reconceptualization of materiality offered here makes it possible to take the empirical world seriously once again, but this time with the understanding that the objective referent is phenomena, not the seeming "immediately given-ness" of the object world.[32]

All bodies, not merely "human" bodies, come to matter through the world's iterative intra-activity—its performativity. This is true not only of the surface or contours of the body but also of the body in the fullness of its physicality, including the very "atoms" of its being. Bodies are not objects with inherent boundaries and properties; they are material-discursive phenomena. "Human" bodies are not inherently different from "nonhuman" ones. What constitutes the human (and the nonhuman) is not a fixed or pregiven notion, but neither is it a free-floating ideality. What is at issue is not some ill-defined process by which human-based linguistic practices (materially supported in some unspecified way) manage to produce substantive bodies or bodily substances, but rather the dynamics of intra-activity in its materiality: material apparatuses produce material phenomena through specific causal intra-actions, where "material" is always already material-discursive—*that is what it means to matter*. Theories that focus exclusively on the materialization of human bodies miss the crucial point that the very practices by which the differential boundaries of the human and the nonhuman are drawn are always already implicated in particular materializations. The differential constitution of the human (nonhuman) is always accompanied by particular exclusions and always open to contestation. This is a result of the nondeterministic causal nature of agential intra-actions, a crucial point that I take up in the section on agency and causality hereafter.

BODILY BOUNDARIES

> What is the outline? . . . it is not something definite. It is not, believe it or not, that every object has a line around it! There is no such line.
>
> —FEYNMAN ET AL., *Feynman Lectures on Physics*

> If one really thinks about the body as such, there is no possible outline of the body as such.
>
> GAYATRI SPIVAK, "In a Word"

The question of bodily boundaries haunts Bohr's account. While Bohr seems to take for granted the givenness of the outside boundary of the apparatus, his conception of the knower is riddled with unresolved ambiguities that unsettle what seemed to be settled. On the one hand, Bohr conceives of the experimenter as an outside observer, a liberal humanist subject who freely chooses among possible apparatuses and then stands back and notes the resulting marks on bodies, which can be unambiguously communicated to fellow scientists as a consequence of the specific embodiment of particular human concepts in the apparatus. This conception of the knowing subject is the basis for Bohr's intersubjective notion of objectivity; the human subject is the finite limit holding back the threat of infinite regress. On the other hand, Bohr argues against the Cartesian presupposition that there is an inherent boundary between observer and observed, knower and known. That boundary is differently articulated depending on the specific configuration of the apparatus and its corresponding embodiment of particular concepts to the exclusion of others. That is, the object and the agencies of observation are co-constituted through the enactment of a cut that depends on the specific embodiment of particular human concepts. Where does this leave the human subject? Inside the phenomenon? As part of the apparatus? On the outside looking in? Is the subject a part of the agencies of observation that emerge through specific intra-actions, or is the subject an outside observer that chooses the apparatus? Human concepts are clearly embodied, but human subjects seem to be frustratingly and ironically disembodied. No wonder the ambiguity isn't resolvable. Is the liberal humanist subject that haunts Bohr's account a Cartesian subject after all?

In this section, I review a small sampling of a multitude of challenges to the individualistic conception of bodies and the presumed givenness of bodily boundaries. This discussion is intended to serve as a backdrop for clarifying the nature of my proposed agential realist intervention. In the next section, I return to the quandary posed by Bohr's humanism and the related question of where the apparatus ends.

Interestingly, Bohr addresses the question of the boundary between subject and object directly in one of his less-technical examples intended for a general audience. He explains complementarity by considering two mutually exclusive ways for a person in a dark room to usefully intra-act with a stick or cane: one possibility is for the person to use the stick to negotiate his way around the room by holding the stick firmly in his hands, in which case the stick is properly understood to be part of the "subject," or he can instead choose to hold the stick loosely to sense its features, in which case the stick is the "object" of observation:

> One need only remember here the sensation, often cited by psychologists, which every one has experienced when attempting to orient himself in a dark room with a stick. When the stick is held loosely, it appears to the sense of touch to be an object. When, however, it is held firmly, we lose the sensation that it is a foreign body, and the impression of touch becomes immediately localized at the point where the stick is touching the body under investigation. (Bohr 1963a [1929 essay], 99)

The mutual exclusivity of these two different practices is evident.[33] The stick cannot usefully serve as an instrument of observation if one is intent on observing it. The line between subject and object is not fixed, but once a cut is made (i.e., a particular practice is being enacted), the identification is not arbitrary but in fact materially specified and determinate for a given practice. It is important to keep in mind that Bohr is making a point about the inherent ambiguity of bodily boundaries and the resolution of those boundaries through particular complementary cuts/practices. He is not making a point about the nature of conscious subjective experience, that is, about phenomena in the phenomenologist's sense.[34]

Now, the objection might be raised that the outside boundary of a person (as well as a stick) is in fact determinate and that the question of whether or not the "subject" includes the stick is really only a pedantic musing and not a substantive issue; that is, at best, it is an example about the nature of human experience and not about the nature of "external" reality. But there is another way to understand the point of this example: what is at issue is differential material embodiment (and not merely of humans), not in the sense of the conscious subjective experience of the individual human subject but in terms of different material configurations of ontological bodies and boundaries, where the actual matter of bodies is what is at issue and at stake. Let's briefly consider some significant challenges to the individualistic and mechanistic conception of the nature of embodiment.

At first glance, the outside boundary of a body may seem evident, indeed incontrovertible. A coffee mug ends at its outside surface just as surely as people end at their skins. On the face of it, reliance on visual clues seems to constitute a solid empirical approach, but are faces and solids really what they seem? In fact, an abundance of empirical evidence from a range of different disciplines, considerations, and experiences strongly suggests that visual clues may be misleading. What may seem evident to some is not simply a result of how things are independently of specific practices of seeing and other bodily engagements with the world. Rather, it has become increasingly clear that the seemingly self-evidentiary nature of bodily boundaries, including their seeming visual self-evidence, is a result of the repetition of (culturally and historically) specific bodily performance. In point of fact, the twentieth century has witnessed serious scientific, philosophical, anthropological, and experiential contestations of this seemingly self-evident point of view. Neurophysiologists, phenomenologists, anthropologists, physicists, postcolonial, feminist, queer, science, and disability studies scholars, and psychoanalytic theorists are among those who question the mechanistic conception of embodiment and the presumably inherent nature of bodily boundaries—especially human ones. Cyborg theorists are among those who find it deeply ironic to stop there.[35]

For example, scientists studying the nature of sight have called attention to the fact that there is much more to the question of where a body ends than meets the eye. In contemplating the physical mechanism of sight, the Nobel laureate physicist Richard Feynman calls into question the alleged inherent and self-evidentiary nature of bodily boundaries:

> The fact that there is an enhancement of contours [in the workings of the visual systems of particular animals, including humans] has long been known; in fact it is a remarkable thing that has been commented on by psychologists many times. In order to draw an object, we have only to draw its outline. How used we are to looking at pictures that have only the outline! What is the outline? The outline is only the edge difference between light and dark or one color and another. *It is not something definite. It is not, believe it or not, that every object has a line around it! There is no such line.* It is only in our own psychological makeup that there is a line. (Feynman 1964, 1:36–11; italics mine)

Feynman understands the mistaken belief in the givenness of bodily boundaries to be an artifact of human psychology. But there's no stopping there: physics tells us that edges or boundaries are not determinate either ontologically or visually. When it comes to the "interface" between a coffee mug and a hand, it is not that there are x number of atoms that belong to a hand and y number of atoms that belong to the coffee mug. Furthermore, as we have seen, there are actually no sharp edges visually either: it a well-recognized fact of physical optics that if one looks closely at an "edge," what one sees is not a sharp boundary between light and dark but rather a series of light and dark bands—that is, a diffraction pattern.[36]

Evidence for the claim that seeing is an achievement that results from specific bodily engagements with the world, and is not merely the inevitable result of the integrity of the visual apparatus (including the optics of the eye, specific neurological sites in the brain, and appropriate connections between them), comes from multiple investigations of human and nonhuman sight. For example, there are documented accounts of individuals who are born blind or lose sight at an early age and receive reparative operations later in life with the goal of restoring their sight only to discover that even after the restoration of the integrity of the visual apparatus, sight does not immediately follow. A careful review of the literature on the perception of space and shape conducted by M. von Senden (1960) in 1932 already notes this phenomenon. Richard Gregory and Jean G. Wallace (1963), and Oliver Sacks (1993) (working with Richard Gregory), have also studied sight restoration.

These accounts all attest to the fact that the notions of objects, faces, space, size, distance, and depth perception are meaningless to a person who has never seen before. Clearly, we do not see merely with our eyes. Interacting with (or rather, intra-acting "with" and as part of) the world is part and parcel of seeing. Objects are not already there; they emerge through specific practices.[37]

Some of the more vivid examples of the inherent indeterminacy of bodily boundaries arise in relation to prosthetic enhancements of disabled bodies. These analyses are often useful not only in helping us to understand prosthetic embodiment but also in enabling us to see taken-for-granted features of "normal" embodiment.

Phenomenologists like Foucault's teacher Maurice Merleau-Ponty argue that the successful performance of everyday bodily tasks depends on the mutual incorporation of the instruments used to perform a task into the body and the dilation of our "being-in-the-world" into the instrument, thereby undermining the taken-for-granted distinction between the inside and outside of the body. Interestingly, Merleau-Ponty takes up virtually the same example that Bohr uses: a blind man who uses a stick to navigate aspects of his local surroundings.[38] Merleau-Ponty notes that in such a case,

> the blind man's stick has ceased to be an object for him, and is no longer perceived for itself; its point has become an area of sensitivity, extending the scope and active radius of touch, and providing a parallel to sight. In the exploration of things, the length of the stick does not enter expressly as a middle term. . . . To get used to a hat, a car or a stick is to be transplanted into them, or conversely, to incorporate them into the bulk of our own body. Habit expresses our power of dilating our being-in-the-world, or changing our existence by appropriating fresh instruments. (Merleau-Ponty 1962, 143)

Similar points have been made by some disabled people and advocates of disability rights. In commenting on Nancy Mairs's *Waist-High in the World*, Lisa Diedrich explains that the wheelchair that Mairs "uses," "a compact electric model called a Quickie P100,"

> is not only an extension of her body or "a bodily auxiliary," as Merleau-Ponty calls a blind person's cane, but has become incorporated, made a part of her body—so much so that when the Quickie P100 breaks down, it is the breakdown not simply of an instrument employed by the body but of Mairs's very self. According to Mairs, "the wheelchair I experience is not 'out there' for me to observe, any more than the rest of my body, and I'm invariably shocked at

the sight of myself hunched in its black framework of aluminum and plastic" (p. 46). In her Quickie P100, Mairs is at one and the same time positioned and situated in the world. (Diedrich 2001, 218–19)

Diedrich points out that for Mairs the Quickie P100 is not merely a bodily auxillary but an integral part of Mairs's body. I want to suggest that there may be important intertwined ontological and ethical points to be made here that go beyond the question of the nature of individual subjective human experience. Diedrich emphasizes the importance of these questions not only to the daily lives of people who have recognized disabilities but also for "able-bodied" people. Those in the latter category (at least up to this point in their lives) often tend to be unreflective about these issues. The luxury of taking for granted the nature of the body as it negotiates a world constructed specifically with an image of "normal" embodiment in mind is enabled by the privileges of ableism. It is when the body doesn't work—when the body "breaks down" —that such presuppositions generally surface. It is often only when things stop working that the apparatus is first noticed. When such (in)opportunities arise the entangled nature of phenomena and the importance of the agential cut and their corollary constitutive exclusions emerges. It then becomes clear that "able-bodiedness" is not a natural state of being but a specific form of embodiment that is co-constituted through the boundary-making practices that distinguish "able-bodied" from "disabled." Focusing on the nature of the materiality of able bodies as phenomena, not individual objects/subjects, makes it clear what it means to be able-bodied: that the very nature of being able-bodied is to live with/in and as part of the phenomenon that includes the cut and what it excludes, and therefore, that what is excluded is never really other, not in an absolute sense, and that in an important sense, then, being able-bodied means being in a prosthetic relationship with the "disabled." How different ethics looks from the vantage point of constitutive entanglements. What would it mean to acknowledge that the "able-bodied" depend on the "disabled" for their very existence? What would it mean to take on that responsibility? What would it mean to deny one's responsibility to the other once there is a recognition that one's very embodiment is integrally entangled with the other?[39]

As we have seen, the question of the nature of embodiment is not a mere artifact of the new technologies but arises from examples closer to hand. Nonetheless some newer technologies have a way of bringing the issues into greater relief. Consider, for example, Sandy Stone's description of encountering Stephen Hawking at a lecture given at the University of California, Santa Cruz.[40]

Hawking has become a legend in his own time, not only for his remarkable contributions to physics but also because he has continued to be an extraordinarily productive physicist during his long-term struggle with ALS (Lou Gehrig's disease). Unable to speak because of the debilitating effects of the disease, Hawking communicates through an artificial speech device called a Votrax. As Stone describes the event, the auditorium where Hawking is speaking is filled to the brim, and loudspeakers have been placed out on the lawn, where a "zillion" people have gathered to listen. She suddenly decides that she doesn't want to sit outside listening to a PA system, and so she sneaks into the auditorium so that she can "actually hear Hawking give the talk." She worms her way inside and manages to get a front-row seat. Stone offers this description of her experience:

> And there is Hawking. Sitting, as he always does, in his wheelchair, utterly motionless, except for his fingers on the joystick of the laptop; and on the floor to one side of him is the PA system microphone, nuzzling into the Votrax's tiny loudspeaker.
>
> And a thing happens in my head. Exactly where, I say to myself, is Hawking? Am I any closer to him now than I was outside? Who is it doing the talking up there on the stage? In an important sense, Hawking doesn't stop being Hawking at the edge of his body. There is the obvious physical Hawking, vividly outlined by the way our social conditioning teaches us to see a person as a person. But a serious part of Hawking extends into the box in his lap. No box, no discourse; Hawking's intellect becomes a tree falling in the forest with nobody around to hear it. Where does he stop? Where are his edges?

"Why should our bodies end at the skin, or include at best other beings encapsulated by skin?" asks the author of "The Cyborg Manifesto." Echoing the phenomenologists while pressing their insights further, Haraway argues that the insistence that there is an obvious bodily boundary that ends at the skin fails to recognize the body's specific situatedness in the world. But for Haraway, "situation is never self-evident, never simply 'concrete,' [but] always critical," "the kind of standpoint with stakes in showing how 'gender,' 'race,' or any structured inequality in each interlocking specific instance gets built into the world—i.e., not 'gender' or 'race' as attributes or as properties, but 'racialized gender' as a practice that builds worlds and objects in some ways rather than others, that gets built into objects and practices and exists in no other way. Bodies in the making, not bodies made."[41] For Haraway, "embodiment is about significant prosthesis" (1991, 195)—bodies in the making are never separate from their apparatuses of bodily production.

In what follows, I use Bohr's crucial insight about the production of bodily boundaries to argue that his liberal humanist conception of human bodies and subjects is in fact untenable, and I propose instead a posthumanist understanding of the "human." Crucially, I will argue that the nature of the production of bodily boundaries is not merely experiential, or merely epistemological, but ontological—what is at issue and at stake is a matter of the nature of reality, not merely a matter of human experience or human understandings of the world. Beyond the issue of how the body is positioned and situated in the world is the matter of how bodies are constituted along with the world, or rather, as "part" of the world (i.e., "being-of-the-world," not "being-in-the-world"). That is, the central issue for my purposes concerns the nature of the body's materiality. I will argue that matter itself entails *entanglements*—that this is its very nature. By "entanglement" I don't mean just any old kind of connection, interweaving, or enmeshment in a complicated situation. Crucially, my use of this term goes to the agential realist ontology that I propose with all its requisite refigurings of causality, materiality, agency, dynamics, and topological reconfigurings. (For an important technical discussion of entanglement, see chapter 7.) Furthermore, I argue that ethics is not simply about responsible actions in relation to human experiences of the world; rather, it is a question of material entanglements and how each intra-action matters in the reconfiguring of these entanglements, that is, it is a matter of the ethical call that is embodied in the very worlding of the world. Intrinsic to these concerns is the question of the boundaries of nonhumans as well as humans and how these differential boundaries are co-constituted, including situations where there are no "humans" around. (See chapter 8 for a detailed discussion of the ethical implications.) In the remainder of this section and the next, I turn my attention again to the question of the boundaries of the apparatus.

Bohr is on questionable grounds in presuming an intrinsic outside boundary to the apparatus, for *his own argument* in fact undermines such a presupposition. In Bohr's account, one is not entitled to presume that an object has determinate boundaries and properties in the absence of their specification through the larger material arrangement. The boundaries and properties of an "object" are determinate only within and as part of a particular phenomenon. Therefore, by the logic of Bohr's own analysis, the boundaries and properties of an apparatus are not well defined outside its determination within a larger phenomenon.

Let's look at this point more closely. Bohr insists that an "unambiguous [i.e., objective] account of proper quantum phenomena must, in principle, include a description of all relevant features of the experimental arrangement" (Bohr 1963c [1958 essay], 4). Now, to determine all its relevant features, it is necessary to characterize the entire experimental apparatus (or at

least all the features that are relevant) by involving it within a larger phenomenon. That is, the apparatus that is to be characterized (i.e., measured) must be the "object of observation" within some larger phenomenon involving its intra-action with an auxiliary apparatus. This is necessary so that the "object apparatus" within the larger phenomenon effects its marks on another "part" of the larger phenomenon (which includes the auxiliary apparatus). In other words, to measure its characteristics (as part of a larger phenomenon), the original apparatus in question would have to become the "object" of investigation in its intra-action with an auxiliary apparatus, thereby involving it in some larger phenomenon. Since it is not possible for the apparatus to simultaneously be both measured object and measuring instrument, the apparatus cannot be fully characterized and function according to its ("original") purpose simultaneously.[42] Or to put it another way, any attempt to measure the "original" apparatus's characteristics will require its involvement within a larger phenomenon whereby it is positioned as the object of investigation, thereby excluding its role as an agency of observation. The measurement of the apparatus entails a different phenomenon from the original one, and the connection of the two different phenomena would require a third, yet larger phenomenon entailing these. Hence the "outside" boundary, like the "inside" boundary, is not determinate in the absence of its involvement in a larger phenomenon. In other words, *there are no intrinsic boundaries*, and even what is "inside" and what is "outside" are intrinsically indeterminate. The logic of Bohr's own argument undercuts the conception of the apparatus as a static and bounded laboratory setup and the human as the set designer, interpreter, and spokesperson for the performance of nature.

THE BOUNDARIES OF AN APPARATUS, OR "CECI N'EST PAS UNE CIGAR"

The demonstration of space quantization, carried out in Frankfurt, Germany, in 1922 by Otto Stern and Walther Gerlach, ranks among the dozen or so canonical experiments that ushered in the heroic age of quantum physics. Perhaps no other experiment is so often cited for elegant conceptual simplicity. From it emerged both new intellectual vistas and a host of useful applications of quantum science. Yet even among atomic physicists, very few today are aware of the historical particulars that enhance the drama of the story and the abiding lessons it offers. Among the particulars are a warm bed [and] a bad cigar. . . .

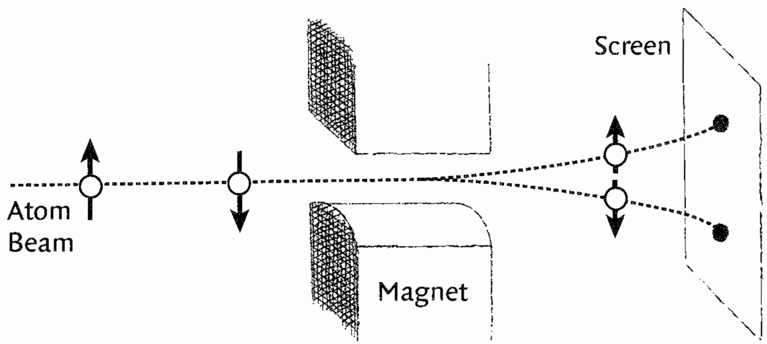
—BRETISLAV FRIEDRICH AND DUDLEY HERSCHBACH, "Stern and Gerlach"[43]

It was during a period in the history of physics known as the time of the "old quantum theory"—an era of scientific uncertainty during the first quarter of the twentieth century when physicists tried on all manner of hybrid notions dressing up a dignified, proper, and stately classical physics with new-fangled quantum ideas—that Otto Stern convinced Walther Gerlach to perform a tedious experiment that Stern believed "if successful, would decide unequivocally between the quantum theoretical and classical views."[44] This is a period marked by Bohr's Nobel Prize–winning model of the atom. Bohr's ingenious application of the new quantum ideas to matter enabled him to provide explanations for both the stability of the atom and the atomic spectrum of hydrogen. In Bohr's model, an atom is a "tiny solar system" with a central nucleus surrounded by a discrete set of concentric electron "orbitals." The observed hydrogen spectrum can be explained by taking account of all possible electron "jumps"—that is, "quantum leaps"—from one discrete orbital (i.e., energy level) to another.[45] Despite the successes of the Bohr model and its extension by Sommerfeld and Debeye, and other triumphs of the old quantum theory, including Einstein's Nobel Prize–winning explanation of the photoelectric effect (which introduced the notion of a photon, or light quantum, into physics), physicists were understandably hesitant to give up so quickly on classical physics, which had proved to be an extraordinarily successful explanatory framework for much of the rest of physical phenomena, from the realm of the heavenly bodies to the everyday and smaller, until certain explorations of the atomic domain got under way.[46] Within this hybrid and rapidly evolving worldview, the Bohr-Sommerfeld-Debeye model of the atom presented a particular puzzle that spawned significant debate: what explanation could be given for the fact that the orientation of the plane of the electron orbit is limited to discrete values, meaning that only particular orientations in space are allowed? Questions about whether this phenomenon, dubbed "space quantization," was a real phenomenon or whether it merely symbolized some other phenomenon not yet understood plagued physicists. The Stern-Gerlach experiment dared to understand space quantization as a real phenomenon (against the grain of the majority opinion). Stern felt that if one could demonstrate the reality of a phenomenon so profoundly nonclassical as space quantization, then classical theory would have to yield to a new physics.[47]

Stern's idea for the experiment crystallized during his meditations on a chilly morning "too cold to get out of bed." The essence of the idea that sparked his imagination was to use magnetism as a probe of space quantization. His experimental design is based on the following conceptual model: an orbiting electron should produce a tiny magnetic field, which would thereby provide a handle for the manipulation of the atom through its interaction with an external magnetic field. In particular, it occurred to Stern that by using a particular arrangement of magnets, one could, in theory, display the discrete orientations of the planes of the orbiting electrons by taking advantage of their different alignments with the external field to separate the electrons with different orientations. He proposed to use a beam of silver atoms and an external field configuration such that the two possible orientations of the electrons orbiting the nucleus of the silver atoms would follow separate paths—electrons with one orientation relative to the magnetic field would be deflected upward, and electrons with the opposite orientation would be deflected downward. In other words, the beam of silver atoms passing through the external field created by the magnets would be split in two, leaving two separate traces on the detecting screen, which was a glass plate (figure 14).

Stern enlisted the experimental talents of Walther Gerlach, who was performing atomic beam experiments in the building adjacent to Born's Institute of Theoretical Physics in Frankfurt, where Stern worked. Conveniently, Gerlach had a magnetic apparatus that suited Stern's purposes. While Stern's idea was straightforward enough, its practical realization was a complex, arduous, and tedious matter. One of Gerlach's students left the following testimony to the trials his professor had to overcome:

> Anyone who has not been through it cannot at all imagine how great were the difficulties with an oven to heat the silver up . . . within an apparatus which could not be fully heated [the seals would melt] and where a vacuum . . . had to be produced and maintained for several hours. . . . The pumps were made of glass and quite often they broke, either from the thrust of boiling mercury . . . or from the dripping of condensed water vapor. In that case the several day effort of pumping, required during the warming up and heating of the oven, was lost. Also, one could be by no means certain that the oven would not burn through during the four- to eight-hour exposure time. Then both the pumping and the heating of the oven had to be started from scratch. It was a Sisyphus-like labor and the main load and responsibility was carried on the broad shoulders of Professor Gerlach. . . . He would get in about 9 p.m. equipped with a pile of reprints and books. During the night he then read the proofs and reviews, wrote papers, prepared lectures, drank plenty of cocoa or tea and smoked a lot. When I arrived the next day at the Institute, heard the intimately familiar noise of the running pumps, and found Gerlach still in the lab, it was a good sign: nothing broke during the night. (W. Schütz, quoted in Friedrich and Herschbach 1998, 179)



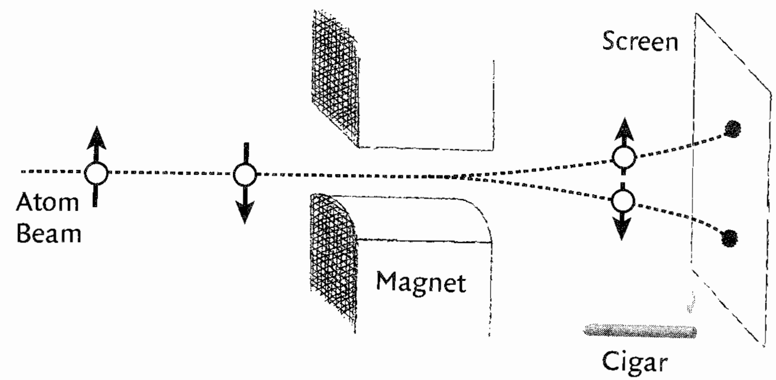
14 Schematic of the Stern-Gerlach experiment. *Illustration by Nicolle Rager Fuller for the author.*

Not only did the success of the experiment require the tenacity and skills of Gerlach's labors, but it also depended on a convergence of other factors: "Among the particulars are a warm bed, a bad cigar, a timely postcard, a railroad strike, and an uncanny conspiracy of Nature" (Friedrich and Herschbach 2003). One of the key factors was external funding from the German American Henry Goldman (a founder of Goldman Sachs and the progenitor of the Woolworth chain of stores). Goldman's contributions were crucial to sustaining Gerlach's research in the face of the increasing financial disarray of the German economy.[48] Einstein was also instrumental, providing a grant from his institute in Berlin to support their efforts.

As fate would have it, the traces of space quantization did not reveal themselves to Gerlach. However, as Stern recounts, there was a particular incident concerning this arduous scientific adventure that would leave its mark on him:

> After venting to release the vacuum, Gerlach removed the detector flange. But he could see no trace of the silver atom beam and handed the flange to me. With Gerlach looking over my shoulder as I peered closely at the plate, we were surprised to see gradually emerge the trace of the beam. . . . Finally we realized what [had happened]. I was then the equivalent of an assistant professor. My salary was too low to afford good cigars, so I smoked bad cigars. These had a lot of sulfur in them, so my breath on the plate turned the silver into silver sulfide, which is jet black, so easily visible. It was like developing a photographic film. (Friedrich and Herschbach 1998, 178–79)

The results Gerlach held in his hand were close, but no cigar! The traces only gradually emerged when Stern held the plates in *his* hands and studied



15 A next-order iteration of the schematic of the Stern-Gerlach experiment, revised to more accurately account for the nature of the apparatus. This schematic includes the crucial agential contribution of the cigar. The reproducibility of the experiment depends on the cigar's presence. Not any old cigar will do: the high sulfur content of a cheap cigar is crucial. Class, nationalism, gender, and the politics of nationalism, among other variables, are all part of this apparatus (which is not to say that all relevant factors figure in the same way or with the same weight). *Illustration by Nicolle Rager Fuller for the author.*

them at a distance close enough so that the plates could absorb the fumes of Stern's sulfuric breath, turning the faint, nearly invisible, silver traces into jet black silver sulfide traces.[49] The magical success of this historic experiment depended on a cheap (cigar) trick (figure 15). If it hadn't been for Stern's tobacco habit coupled with his relative impoverishment, the duo might have given up hope of finding any trace of space quantization, which refused to show itself in the absence of a little helpful cajoling from the cigar's sulfurous fumes.[50]

As the example of Otto Stern's cheap cigar makes quite poignant, taking for granted that the outside boundary of the apparatus ends at some "obvious" (visual) terminus, or that the boundary circumscribes only that set of items we learn to list under "equipment" in laboratory exercises in science classes, trusting our classical intuition, our training, and everyday experience to immediately grasp the "apparatus" in its entirety, makes one susceptible to illusions made of preconceptions, including "the obvious" and "the visible," thereby diverting attention from the reality of the role played by smoke and mirrors (or at least smoke, glass, and silver atoms), where the "smoke screen" itself is a significant part of the apparatus.[51]

Significantly, the Stern-Gerlach experiment did not in fact yield the expected result, nor was it as definitive as Stern had hoped. Although Stern remarked that the success of their experiment would "decide unequivocally between the quantum theoretical and classical views," what the textbook accounts don't mention is that a preliminary report by Stern and Gerlach did not show evidence of beam splitting. That is, the initial results did not support the quantum worldview as Stern understood it. And yet *this* result was not taken to be definitive of a negative result:

> A preliminary result reported by Stern and Gerlach did not show splitting of the beam into components. It did, however, show a broadened beam spot. They concluded that although they had not demonstrated spatial quantization, they had provided "evidence that the silver atom possesses a magnetic moment." (A. Franklin 2002)

That is, they did not conclude that spatial quantization is not a real effect after all (and definitively so). Instead "Stern and Gerlach made improvements in the apparatus, particularly in replacing a round beam slit by a rectangular one that gave a much higher intensity" (ibid.). And this idea paid off in spades: this relatively minor reconfiguring of the apparatus resolved the broadened beam spot into two components, entirely reworking their conclusion.[52] But that's not where the irony concerning this allegedly field-defining experiment stops. Although virtually every quantum physics textbook hails the Stern-Gerlach experiment as a definitive and straightforward result (push a button and note what happens), it was only years afterward that the results were given their current interpretation: Stern and Gerlach had produced evidence not for space quantization but for the existence of the spin (angular momentum) of the electron.

> Practically all current textbooks describe the Stern-Gerlach splitting as demonstrating electron spin, without pointing out that *the intrepid experimenters had no idea it was spin that they had discovered*. . . . The gratifying agreement of the Stern-Gerlach splitting with the old theory proved to be *a lucky coincidence*. . . . Nature thus was duplicitous in an uncanny way. (Friedrich and Herschbach 2003; rearranged, italics mine)[53]

Recently, a new center for experimental physics at the University of Frankfurt was named for Stern and Gerlach. The memorial plaque for the center uses the imagery of the split beam to show Stern and Gerlach on opposite sides, symbolizing the opposite directions taken by the two physicists as a result of Hitler's rise to power.[54] Not unlike the strain that resulted on the relationship of Bohr and Heisenberg, Stern and Gerlach's relationship suf-

fered from their differing positions during the war. Stern, like Bohr, was Jewish and was forced to emigrate. Gerlach, like Heisenberg, remained in Germany during the war. And like Heisenberg, Gerlach played a major role in wartime efforts to develop a nuclear bomb for Germany. In fact, Gerlach, whose reputation was greatly enhanced by his work on the famed Stern-Gerlach experiment, was appointed head of the Reich's nuclear research program and was one of the ten leading German scientists (along with Heisenberg) detailed at Farm Hill by the Allied forces after the war.[55]

Apparatuses are not static laboratory setups but a dynamic set of open-ended practices, iteratively refined and reconfigured. As the revised diagram of the Stern-Gerlach apparatus indicates, a cigar is among the significant materials that are relevant to the operation and success of the experiment (see figure 15). Not any cigar will do. Indeed, the cigar is a "condensation"—a "nodal point," as it were—of the workings of other apparatuses, including class, nationalism, economics, and gender, all of which are a part of this Stern-Gerlach apparatus. Which is not to say that all relevant factors figure in the same way or with the same weight. The precise nature of this configuration (i.e., the specific practices) matters. Nor is it to suggest that social factors determine the outcome of scientific investigations. Indeed, it would be a mistake to understand the presence of the cigar in the diagram as a symbol of the fact that the experimenter's intrinsic identity (e.g., his gender and class) is a determining factor in the outcome of the experiment. This reading would be mistaken in several important ways: it misunderstands the nature of gender, class, individuals, practices, materiality, agency, and causality. (And, yes, of course, a woman smoking the same kind of cigar for the same length of time and breathing with the same sulfurous breath on the same plate would have obtained the same result. Far be it for any feminist to suggest otherwise. Nor is the point that women are less likely to smoke cigars, even cheap ones.) The point is, rather, that in this case, material practices that contributed to the production of gendered individuals also contributed to the materialization of this particular scientific result ("gender-and-science-in-the-making"): "objects" and "subjects" are coproduced through specific kinds of material-discursive practices. Stern's gendered and classed performance of masculinity (e.g., through his cigar smoking) mattered. (This is not to suggest that the smoking of cheap cigars was the only possible contingency that could have helped to serendipitously develop the plate, but it was a factor, like many other factors, in the discovery of this result.) The point is not that there are leaks in the system where social values seep in despite scientists' best efforts to maintain a vacuum-tight seal between the separate domains of nature and culture. Nor should we conclude that the quality of the results is diminished in proportion to the permeability of this barrier. This kind of thinking mistakenly reifies culture and nature and gender and science into separate categories. But the fact is that the world isn't naturally broken up into social and scientific realms that get made separately. There isn't one set of material practices that makes science, and another disjunct set that makes social relations; one kind of matter on the inside, and another on the outside. The social and the scientific are co-constituted. They are made together—but neither is just made up. Rather, they are ongoing, open-ended, entangled material practices. The goal is therefore to understand which specific material practices matter and how they matter. What we find in this particular case is that gender performativity, among other important factors including nature's performativity, was a material factor in this scientific outcome.[56]

This example not only illustrates the dynamic nature of scientific practices and the lack of a determinate outside boundary to the apparatus but also clearly suggests that humans enter not as fully formed, preexisting subjects but as subjects intra-actively co-constituted through the material-discursive practices that they engage in. I will explore this suggestion further in the next section.

THE NATURE OF AN APPARATUS AND A POSTHUMANIST ROLE FOR THE "HUMAN"

Physicists and poststructuralists offer very different reasons for their mutual rejection of humanism. As far as physicists are concerned, the human has no place in a respectable physical theory that claims to explain the workings of nature. Indeed, it is the distasteful centrality of human interventions in the form of conceptual frameworks and measuring instruments—the artifactual contrivances of laboratory exercises—in the foundations of quantum physics that constitutes the basis for the most common complaints against Bohr's interpretation of quantum mechanics.[57] Poststructuralists, on the other hand, object to the liberal humanist prejudice that positions the subject as fully constituted before its engagement in social practices. The defect here lies in the elision of the role of power in the very constitution of the "subject."[58] In both cases, the offending humanist elements are linked to a failure to account for the practices through which boundaries are produced, including an examination of how the constitutive exclusions of boundary-making practices matter.

Significantly, each of these critical perspectives is entangled in its own

anthropocentrisms. While Foucault's genealogical analysis focuses on the production of human bodies, to the exclusion of nonhuman bodies whose constitution he takes for granted, Bohr is attentive to the production of nonhuman phenomena and takes for granted the prior existence of a human observer. Paradoxically, the latter assumption is not a difficulty for many of Bohr's critics who would jettison the human observer from the physical universe altogether, staging him in some exterior position as the condition for the possibility of objective knowledge—hence ironically according the human a unique position among physical systems.[59] Each of these formulations presumes human-nonhuman, nature-culture, and social-scientific dichotomies. Each stops short of understanding humans and nonhumans in their mutual constitution, as integral parts *of* the universe—not as beings *in* the universe.

As we have seen, apparatuses are not inscription devices, scientific instruments set in place before the action happens, or machines that mediate the dialectic of resistance and accommodation between human and nonhuman laboratory actors. Apparatuses do not possess inherent outside boundaries limiting them to laboratory spaces or experimental practices.[60] Indeed, a given apparatus need not be specifically implicated in any practice that goes by the name "scientific." But neither are they to be understood purely as technologies of the social (as opposed to the natural) in the sense suggested by theorists of political and social practices (following either Althusser or Foucault, for example, in their very different uses of the term). It is worth noting the degree to which these scholars exclude "scientific" practices in their consideration of "social" practices, and likewise the degree to which many scholars who write about scientific practices exclude relevant social dimensions (including self-avowed social constructivists and actor network theorists who neglect crucial social variables and relations of power such as those related to race, gender, and sexuality).[61] Apparatuses are neither neutral probes of the natural world nor social structures that deterministically impose some particular outcome. Significantly, in an agential realist account, the notion of an apparatus is not premised on inherent divisions between the social and the scientific, the human and the nonhuman, nature and culture. Apparatuses are the practices through which these divisions are constituted. This formulation makes it possible to perform a genealogical accounting of the material-discursive practices by which these important distinctions are produced.

In an agential realist account, *apparatuses are specific material configurations, or rather, dynamic (re)configurings of the world through which bodies are intra-actively* *materialized*. That is, apparatuses are the practices of mattering through which intelligibility and materiality are constituted (along with an excluded realm of what doesn't matter). Or to put it another way, apparatuses are material (re)configurings or discursive practices that produce material phenomena in their differential becoming. Phenomena are produced through specific causal intra-actions involving multiple apparatuses of bodily production. Intra-actions are causal (but nondeterministic) enactments through which matter-in-the-process-of-becoming is sedimented out and enfolded in further materializations.[62] That is, apparatuses are *material-discursive practices—causal intra-actions through which matter is iteratively and differentially articulated, reconfiguring the material-discursive field of possibilities and impossibilities in the ongoing dynamics of intra-activity that is agency*. Apparatuses are not bounded objects or structures; they are open-ended practices. The reconfiguring of the world continues without end. Matter's dynamism is inexhaustible, exuberant, and prolific.

In agential realism's reconceptualization of materiality, matter is agentive and intra-active. Matter is a dynamic intra-active becoming that never sits still—an ongoing reconfiguring that exceeds any linear conception of dynamics in which effect follows cause end-on-end, and in which the global is a straightforward emanation outward of the local. Matter's dynamism is generative not merely in the sense of bringing new things into the world but in the sense of bringing forth new worlds, of engaging in an ongoing reconfiguring *of* the world. Bodies do not simply take their places in the world. They are not simply situated in, or located in, particular environments. Rather, "environments" and "bodies" are intra-actively co-constituted. Bodies ("human," "environmental," or otherwise) are integral "parts" of, or dynamic reconfigurings of, what is.[63]

Importantly, apparatuses are themselves phenomena. To take a specifically scientific example, apparatuses are not preformed, interchangeable objects that sit on a shelf waiting to serve a particular purpose, as any experimentalist will confirm. Apparatuses are constituted through particular practices that are perpetually open to rearrangements, rearticulations, and other reworkings. This is part of the creativity and difficulty of doing science: getting the instrumentation to work in a particular way for a particular purpose (which is always open to the possibility of being changed during the experiment as different insights are gained). Furthermore, any particular apparatus is always in the process of intra-acting with other apparatuses, and the enfolding of (relatively) stabilized phenomena (which may be traded across laboratories, cultures, or geopolitical spaces only to find themselves differently materializing) into subsequent iterations of particular practices

constitutes important shifts in the particular apparatus in question and therefore in the nature of the intra-actions that result in the production of new phenomena, and so on. Boundaries do not sit still.

Agential intra-actions are specific causal material enactments that may or may not involve "humans." The question is: what does this "involvement" entail? First, I briefly review some of the difficulties posed by some of the more usual approaches to understanding human subjects; then I will explicate the nature of the posthumanist role of the human.

The contention that apparatuses are productive of phenomena may be the source of some discomfort for those who are accustomed to humanist and antihumanist accounts. Humanist accounts understand this production as a direct consequence of human actions, choices, intentions, commitments, ideas, values, concepts, beliefs, presuppositions, goals, and the like. Contrary to this view, I would argue that determinately bounded and propertied human subjects do not exist prior to their "involvement" in naturalcultural practices. Also problematic is the antihumanist view that encourages, or does not sufficiently discourage, the mistaken belief that human bodies and subjectivities are the effects of human-based discursive practices. Like their humanist counterparts these accounts reinscribe the nature-culture, human-nonhuman, animate-inanimate binaries and other Enlightenment values and stakes that antihumanism seeks to destabilize.

In an agential realist account, human subjects are neither outside observers of apparatuses, nor independent subjects that intervene in the workings of an apparatus, nor the products of social technologies that produce them. Nor is the issue merely a matter of incorporating both humans and nonhumans into the apparatus of bodily production. The point is as follows: to the extent that concepts, laboratory manipulations, observational interventions, and other human practices have a role to play, it is as part of the larger material configuration of the world. That is, the phenomena produced are not the consequences of human will or intentionality or the effects of the operations of Culture, Language, or Power. Humans do not merely assemble different apparatuses for satisfying particular knowledge projects; they themselves are part of the ongoing reconfiguring of the world. The particular configuration that an apparatus takes is not an arbitrary construction of "our" choosing. Which is not to say that human practices have no role to play; we just have to be clear about the nature of that role.[64] Apparatuses are not assemblages of humans and nonhumans; they are open-ended practices involving specific intra-actions of humans and nonhumans, where the differential constitutions of human and nonhuman designate particular phenomena that are themselves implicated in the dynamics of intra-activity, including their enfolding and reconstitution in the reconfiguring of apparatuses.[65] That is, human bodies, like all other bodies, are not entities with inherent boundaries and properties but phenomena that acquire specific boundaries and properties through the open-ended dynamics of intra-activity. Humans are part of the world-body space in its dynamic structuration.

Does this mean that humans have no responsibility for the outcomes of specific practices? If the liberal humanist conception of the subject who chooses a particular apparatus that enacts a cut delineating the object from the agencies of observation is found wanting, does that mean that human subjects are merely pawns in the game of life, victims of the same practices that produce the phenomena being investigated? Are we not back to square one, to the Enlightenment ideal of the detached observer, the modest witness, who intervenes as needed, either willfully or in accordance with some master plan, and when all is said and done simply stands back and watches what temporally emerges? The answer to each of these questions is decidedly no. On the contrary, it is the liberal humanist conception of the subject, not the agential realist one, that encourages the notion that responsibility begins and ends with a willful subject who is destined to reap the consequences of his actions. Agency is not something that humans and even nonhumans have to varying degrees. And agency is not a binary proposition, either on or off. Futhermore, responsibility is not the exclusive right, obligation, or dominion of humans (see later sections in this chapter and chapter 8). To repeat, human subjects do have a role to play, indeed a constitutive role, but we have to be clear about the nature of that role.

An agential realist understanding of the notion of agency entails a significant reworking of the traditional conception. I will discuss this in detail hereafter and respond to the questions concerning responsibility articulated here. But a related question arises that I want to address first: If the human cannot be presumed from the outset and is no longer cemented into the foundations of the theory, then what happens to objectivity? That is, in our undoing of the humanist conception of the subject, haven't we nullified all of Bohr's hard work to secure the objectivity of science, since he places the human at the center of his intersubjective rendering of objectivity? Has objectivity been sacrificed?

OBJECTIVITY AND AGENTIAL SEPARABILITY

Bohr understood the question of objectivity to constitute one of the primary challenges—if not *the* primary challenge—of the new quantum theory. For Bohr, the issue was quite straightforward: if quantum physics teaches us that measurements necessarily entail subjective elements (which enter into the physical considerations by way of their embodiment in apparatuses), then the very possibility of the objectivity of science is at stake. In what follows, I offer a more detailed discussion of how Bohr meets this challenge, and I argue that my ontological rendering of Bohr's notion of phenomenon is the basis for a stronger *ontological* understanding of objectivity, indeed a posthumanist conception, in contrast to Bohr's epistemic human-based rendering.

The sustained and impassioned debate between Bohr and Einstein reached its pinnacle in 1935 when Einstein, Podolsky, and Rosen (EPR) published a paper that was intended to shake physicists' growing confidence in quantum theory.[66] The EPR challenge raises the question of the nature of reality and what quantum mechanics tells us about it. Physicists and philosophers of physics have noted that the EPR paper expresses Einstein's displeasure that quantum mechanics seems to allow spatially separated states to communicate with one another (i.e., exchange information) instantaneously, in seeming violation of the special theory of relativity. Don Howard, a philosopher of science, argues that Einstein's primary concern actually touches on a deeper, more fundamental issue: a violation of the metaphysical commitment to spatial separability. For Einstein, spatial separability is nothing less than the condition for objectivity. Howard explains:

> Like so many realists before him, Einstein speaks of the real world which physics aims to describe as the real "external" world, and he does so in such a way as to suggest that the independence of the real—its not being dependent in any significant way on ourselves as observers—is grounded in this "externality." For most other realists this talk of "externality" is at best a suggestive metaphor. But for Einstein, it is no metaphor. "Externality" is a relation of spatial separation, and the separability principle, the principle of "the mutually independent existence of spatially distant things," asserts that any two systems separated by so much as an infinitesimal spatial interval always possess separate states. Once we realize that observer and observed are themselves just previously interacting physical systems, we see that their independence is grounded in the separability principle along with the independence of all other physical systems. (Howard 1985, 192–93)

In other words, absolute exteriority is the condition of objectivity for Einstein. Spatial separation ensures ontological separability; any two systems spatially separated by so much as an infinitesimal spatial interval always possess separately determinate states.[67] Hence, in Einstein's way of thinking, the spatial separation of observer and observed guarantees their ontological separability and consequently secures the condition for the possibility of objectivity. But if the condition for objectivity—the requisite relation of exteriority between observer and observed as secured by the existence of distinct states of spatially separated systems—is what is being called into question, then objectivity seems to hang precariously in the balance.[68]

Bohr did not find Einstein's concerns troubling because Bohr did not share the same metaphysical beliefs. For Bohr, the so-called instantaneous communication between spatially separated systems is explained by the fact that these allegedly separated states are not really separate at all, but rather "parts" of one phenomenon.[69] Furthermore, for Bohr, objectivity is not secured by spatial separability. For one thing, in Bohr's account, Einstein is not entitled to help himself to spacetime descriptions outside the requisite conditions for their existence. Furthermore, individuation is not a given but the result of specific cuts enacted by the experimental arrangement. Bohr suggests a different set of criteria for objectivity. In Bohr's account, objectivity is a matter of the unambiguous communication of the results of reproducible experiments.[70]

That is, objectivity for Bohr is not a matter of being at a remove from what one is studying, a condition predicated on classical physics' metaphysical belief in individualism, but a question of the unambiguous communication of the results of reproducible experiments. What secures the possibility of reproducibility and unambiguous communication is the Bohrian cut enacted by the apparatus.[71] The crucial point is that when an experiment is performed and the determinate values of the "permanent marks . . . left on bodies" are read by a human observer, an unambiguous description of the phenomenon is made possible by the fact that the apparatus provides both a resolution of the inherent indeterminacy between object and agencies of observation within the resulting phenomenon and a resolution of the inherent semantic indeterminacy, so that there exist well-defined concepts that can be used to objectively describe the results. That is, both the phenomenon and the embodied concepts that are used to describe them are conditioned by one and the same apparatus (which resolves the inherent ambiguities).[72]

Drawing out the ontological dimensions of Bohr's framework provides the possibility of strengthening the notion of objectivity, providing a more robust conception rather than mere intersubjectivity. It also has the added benefit of not depending on a human observer. Significantly, the alternative I propose provides the possibility of removing problematic humanist elements in Bohr's account and avoiding some of the most controversial elements of Bohr's philosophy-physics without sacrificing objectivity.[73] In my agential realist elaboration, what replaces (Einstein's favored) spatial sepa-

rability as the ontological condition for objectivity is *agential separability—an agentially enacted ontological separability within the phenomenon.*[74] Objectivity is not sacrificed with the downfall of metaphysical individualism. No classical ontological condition of absolute exteriority between observer and observed (based on the metaphysics of individuated separate states) is required. The crucial point is that the apparatus enacts an agential cut—a resolution of the ontological indeterminacy—*within* the phenomenon, and *agential separability —the agentially enacted material condition of exteriority-within-phenomena—provides the condition for the possibility of objectivity*. This agential cut also enacts a local causal structure in the marking of the measuring instrument (effect) by the measured object (cause), where "local" means within the phenomenon. If the apparatus is changed, there is a corresponding change in the agential cut and therefore in the delineation of object from agencies of observation and the causal structure (and hence the possibilities for "the future behavior of the system") enacted by the cut. Different agential cuts produce different phenomena. Crucially, then, the apparatus is both causally significant (providing the conditions for enacting a local causal structure) *and* the condition for the possibility of the objective description of material phenomena, pointing toward an important reconciliation of the Cartesian separation of intelligibility and materiality, and all that follows.

The implications of this proposed understanding of the conditions for objectivity are substantial and far-reaching. I discuss these implications following a discussion of the agential realist understanding of agency.

THE NATURE OF PRODUCTION AND THE PRODUCTION OF NATURE: AGENCY AND CAUSALITY

What is the nature of causality according to this account? What possibilities exist for agency, for intra-acting in and as part of the world's becoming? Where do the issues of responsibility and accountability enter in?

Causality is most often figured as a relation between distinct entities. For example, in the interaction between distinct entities the one that modifies (e.g., leaves its mark on) another entity is said to be the cause of the effect left on the other. But according to agential realism, separately determinate entities do not preexist their intra-action. So how are we to think about causality on this account?

On an agential realist account, causal relations cannot be thought of as specific relations between isolated objects; rather causal relations necessarily entail a specification of the material apparatus that enacts an agential cut between determinately bounded and propertied entities within a phenomenon. The larger apparatus (e.g., the specific configuration of barriers, slits, particle sources, and screens) is causally significant. It is not that a preexisting entity receives a mark from a separately determinate entity but rather that the marking or specific materializing "effect" identifies the agencies of observation as agentially separable from its "cause" (the "object") within the phenomenon. The marks left on the agencies of observation (the effect) are said to constitute a measurement of specific features of the object (the cause). In a scientific context, this process is known as a measurement. (Indeed, the notion of measurement is nothing more or less than a causal intra-action.)[75] Whether it is thought of as a measurement, or as part of the universe making itself intelligible to another part in its ongoing differentiating intelligibility and materialization, is a matter of preference.[76] Either way, what is important about causal intra-actions is that "marks are left on bodies": bodies differentially materialize as particular patterns *of* the world as a result of the specific cuts and reconfigurings that are enacted. Cause and effect emerge through intra-actions. Agential intra-actions are causal enactments.

This causal structure differs in significant respects from the common choices of absolute exteriority and absolute interiority and of determinism and free will. Some forms of cultural and social constructivism rely on a geometry of absolute exteriority. For example, in the inscription model of constructivism, culture is figured as an external force acting on passive nature. There is an ambiguity in this model as to whether nature exists in any prediscursive form before its marking by culture. If there is such an antecedent entity, then its very existence marks the inherent limit of constructivism. (In this case, the rhetoric might usefully be softened to more accurately reflect the fact that the force of culture "shapes" or "inscribes" nature but doesn't materially "produce" it.) On the other hand, if there is no preexistent nature, then it behooves those who advocate such a theory to explain how culture can materially produce that from which it is allegedly ontologically distinct, namely, nature. What is the mechanism of this production? The other usual alternative is also not attractive: the geometry of absolute interiority amounts to a reduction of the effect to its cause, or in this case nature to culture, or matter to language, which amounts to one form or another of idealism.

Agential separability presents an alternative to these unsatisfactory options.[77] It rejects the geometries of absolute exteriority or absolute interiority and opens up a much larger space that is more appropriately thought of as a dynamic and ever-changing topology.[78] More specifically, *agential separability* is a matter of *exteriority within phenomena*. Note that since phenomena are material-discursive, no priority is given to either materiality or discursivity; neither one stands outside the other. There is no geometrical relation of absolute exteriority between a "causal apparatus" and a "body effected," or an idealistic collapse of the two, but rather an ongoing topological dynamics of enfolding whereby the spacetimematter manifold is enfolded into itself. This topological dynamics/dynamic topology is a result of matter's dynamism, as I will explain. It may be helpful at this point to take in the fact that the apparatuses of bodily production, which are themselves phenomena, are (also) part of the phenomena they produce: phenomena are forever being reenfolded and reformed.

Crucially, matter plays an agentive role in its iterative materialization. This is an important reason, but not the only reason, that the space of agency is much larger than that postulated in many other critical social theories. Another crucial factor is that the agential realist notion of causality does not take sides in the traditional debates between determinism and free will but rather poses an altogether different way of thinking about temporality, spatiality, and possibility. Intra-actions always entail particular exclusions, and exclusions foreclose the possibility of determinism, providing the condition of an open future.[79] But neither is anything and everything possible at any given moment. Indeed, intra-actions iteratively reconfigure what is possible and what is impossible—possibilities do not sit still. One way to mark this is to say that intra-actions are constraining but not determining. But this way of putting it doesn't do justice to the nature of "constraints" or the dynamics of possibility. Possibilities aren't narrowed in their realization; new possibilities open up as others that might have been possible are now excluded: possibilities are reconfigured and reconfiguring.[80] There is a vitality to the liveliness of intra-activity, not in the sense of a new form of vitalism, but rather in terms of a new sense of aliveness.[81] The world's effervescence, its exuberant creativeness, can never be contained or suspended. Agency never ends; it can never "run out." The notion of intra-actions reformulates the traditional notions of causality and agency in an ongoing reconfiguring of both the real and the possible.

In an agential realist account, agency is cut loose from its traditional humanist orbit. Agency is not aligned with human intentionality or subjectivity. Nor does it merely entail resignification or other specific kinds of moves within a social geometry of antihumanism. The space of agency is not only substantially larger than that allowed for in Butler's performative account, for example, but also, perhaps rather surprisingly, larger than what liberal humanism proposes. Significantly, matter is an agentive factor in its iterative materialization. Furthermore, the future is radically open at every turn, and this open sense of futurity does not depend on the clash or collision of cultural demands. Rather, it is inherent in the nature of intra-activity —even when apparatuses are primarily reinforcing, agency is not foreclosed. Furthermore, the space of agency is not restricted to the possibilities for human action. But neither is it simply the case that agency should be granted to nonhumans as well as humans, or that agency can be distributed over nonhuman and human forms. What is at issue, rather, are the possibilities for the iterative reconfiguring of the materiality of human, nonhuman, cyborgian, and other such forms. Holding the category "human" ("nonhuman") fixed (or at least presuming that one can) excludes an entire range of possibilities in advance, eliding important dimensions of the workings of agency.

Crucially, *agency is a matter of intra-acting; it is an enactment, not something that someone or something has.* It cannot be designated as an attribute of subjects or objects (as they do not preexist as such). It is not an attribute whatsoever. *Agency is "doing" or "being" in its intra-activity. It is the enactment of iterative changes to particular practices—iterative reconfigurings of topological manifolds of spacetime-matter relations—through the dynamics of intra-activity. Agency is about changing possibilities of change entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by those practices in the enactment of a causal structure.* Particular possibilities for (intra-)acting exist at every moment, and these changing possibilities entail an ethical obligation to intra-act responsibly in the world's becoming, to contest and rework what matters and what is excluded from mattering.

Since different agential cuts materialize different phenomena—different marks on bodies—our intra-actions do not merely effect what we know and therefore demand an ethics of knowing; rather, our intra-actions contribute to the differential mattering of the world. *Objectivity means being accountable for marks on bodies, that is, specific materializations in their differential mattering.* We are responsible for the cuts that we help enact not because we do the choosing (neither do we escape responsibility because "we" are "chosen" by them), but because we are an agential part of the material becoming of the universe. Cuts are agentially enacted not by willful individuals but by the larger material arrangement of which "we" are a "part." The cuts that we participate in enacting matter. Indeed, ethics cannot be about responding to the other as if the other is the radical outside to the self. Ethics is not a

geometrical calculation; "others" are never very far from "us"; "they" and "we" are co-constituted and entangled through the very cuts "we" help to enact. Cuts cut "things" together and apart. Cuts are not enacted from the outside, nor are they ever enacted once and for all.

RE(CON)FIGURING SPACE, TIME, AND MATTER

Dynamics are about change. To specify or study the dynamics of a system is to say something about the nature of and possibilities for change. This includes specifying the nature of causation, the nature of the causes that effect change, the possibilities for what can change and how it can change, the nature and range of possible changes, and the conditions that produce change. The study of dynamics, as it is generally conceptualized within the natural sciences, is concerned with how the values of particular variables change over time as a result of the action of external forces, where time is presumed to march along as an external parameter. Agential realism does not simply pose a different dynamics (substituting one set of laws for another); it introduces an altogether different understanding of dynamics. It is not merely that the form of the causal relations has been changed, but the very notions of causality, as well as agency, space, time, and matter, are all reworked. Indeed, in this account, the very nature of change and the possibilities for change changes in an ongoing fashion as part of the world's intra-active dynamism.

Intra-actions are nonarbitrary, nondeterministic causal enactments through which matter-in-the-process-of-becoming is iteratively enfolded into its ongoing differential materialization. Such a dynamics is not marked by an exterior parameter called time, nor does it take place in a container called space. Rather, *iterative intra-actions are the dynamics through which temporality and spatiality are produced and iteratively reconfigured in the materialization of phenomena and the (re)making of material-discursive boundaries and their constitutive exclusions.* Exclusions are constitutive elements of the dynamic interplay (intra-play) of determinacy and indeterminacy. Indeterminacy is never resolved once and for all. Exclusions constitute an open space of agency; they are the changing conditions of possibility of changing possibilities. Where change is not a continuous mutation of what was or the unraveling of what will be, or any kind of continuous transformation in or through time, but the iterative differentiatings of spacetimemattering. In what follows, I elaborate on these claims.

Time is not a succession of evenly spaced individual moments. It is not simply there as substance or measure, a background uniformly available to all beings as a reference or an ontological primitive against which change and stasis can be measured. In my agential realist account, what is at issue is not merely that time and space are not absolute but relative (following Einstein); rather, it is that intra-actions themselves matter to the making/marking of space and time. In other words, spatiality and temporality must also be accounted for in terms of the dynamics of intra-activity.[82]

As discussed in a previous section, materialization is not the end product or simply a succession of intermediary effects of purely discursive practices. Materiality itself is a factor in materialization. The dynamics of mattering are nonlinear: the specific nature of the material configurations of the apparatuses of bodily production, which are themselves phenomena in the process of materializing, matters to the materialization of the specific phenomena of which they are a part, which matters to the ongoing materialization of the world in its intra-active becoming, which makes a difference in subsequent patterns of mattering, and so on; that is, matter is enfolded into itself in its ongoing materialization. The iterative enfolding of specific materializing phenomena into practices of materialization matters to the specifics of the materialization it produces.[83] In short, the iterative enfolding of matter comes to matter. Matter is the sedimenting historiality of practices/agencies *and* an agentive force in the world's differential becoming. Becoming is not an unfolding in time but the inexhaustible dynamism of the enfolding of mattering.

Temporality is constituted through the world's iterative intra-activity. Matter's dynamism is implicated in its production. Temporality is produced through the iterative enfolding of phenomena marking the sedimenting historiality of differential patterns of mattering.[84] As the rings of trees mark the sedimented history of their intra-actions within and as part of the world, so matter carries within itself the sedimented historialities of the practices through which it is produced as part of its ongoing becoming—it is ingrained and enriched in its becoming.[85] Time has a history. Hence it doesn't make sense to construe time as a succession of evenly spaced moments or as an external parameter that tracks the motion of matter in some preexisting space. Intra-actions are temporal not in the sense that the values of particular properties change in time; rather, which property comes to matter is re(con)figured in the very making/marking of time.

Similarly, space is not a collection of preexisting points set out in a fixed geometry, a container, as it were, for matter to inhabit. Matter isn't situated

in the world; matter is worlding in its materiality. What matters is marked off from that which is excluded from mattering but not once and for all. Intra-actions enact specific boundaries, marking the domains of interiority and exteriority, differentiating the intelligible from the unintelligible, the determinate from the indeterminate.[86] Constitutive exclusions open a space for the agential reconfiguring of boundaries. As boundaries are reconfigured, "interior" and "exterior" are reworked. That is, through the enfolding of phenomena, as part of the dynamics of iterative intra-activity, the domains of "interior" and "exterior" lose their previous designations. The boundaries that are enacted are not abstract delineations but specific material demarcations not *in* space but *of* space. Spatiality is intra-actively produced. It is an ongoing process of the material (re)configuring of boundaries—an iterative (re)structuring of spatial relations. Hence spatiality is defined not only in terms of boundaries but also in terms of exclusions.

Space, time, and matter are mutually constituted through the dynamics of iterative intra-activity. The spacetime manifold is iteratively (re)configured in terms of how material-discursive practices come to matter. The dynamics of enfolding involve the reconfiguring of the connectivity of the spacetimematter manifold itself (a changing topology), rather than mere changes in the shape or the size of a bounded domain (geometrical shifts). It should not be presumed that either the manifold itself or changes to the manifold are continuous. Discontinuity plays an important role. Changes do not follow in continuous fashion from a given prior state or origin, nor do they follow some teleological trajectory—there are no trajectories.

The question of the nature of change brings us back around to the metaphor of the tree rings. This metaphor is meant to be evocative of the sedimenting process of becoming. In particular, the point is that the making/marking of time is a lively material process of enfolding. But the metaphor is also limited in several important ways. (In any case it is not to be taken literally as representation; rather, it is offered as an evocation and provocation to think with.) First of all, the point is not that time leaves its mark as it were and marches on, leaving a trail of sedimentation to witness the effects of the external forces of change. Sedimenting is an ongoing process of differential mattering. The past matters and so does the future, but the past is never left behind, never finished once and for all, and the future is not what will come to be in an unfolding of the present moment; rather the past and the future are enfolded participants in matter's iterative becoming (see especially the discussion of the quantum eraser experiment in chapter 7).

Another important limitation is that this metaphor does nothing to interrupt the persistent assumption that change is a continuous process through or in time. But as we have seen the disruption of continuity in the form of a "quantum discontinuity" (a very tiny one indeed) is the source of the disruption of many of the foundational notions of classical physics; indeed it disrupts no less than taken-for-granted notions of space, time, matter, causality, and agency, and epistemology, ontology, and ethics. (The double or paradoxical naming of this discontinuity suggests a disconcerting aporia —what is a discontinuous discontinuity?—should we understand this discontinuity to contain the trace of its own disruption/undoing? In a sense the troubled naming seems quiet apt since a discontinuity that queers our presumptions of continuity cannot be the opposite of the continuous, nor continuous with it.) Quantum leaps aren't jumps (large or small) through space and time. An electron that "leaps" from one orbital to another does not travel along some continuous trajectory from here-now to there-then. Indeed, at no time does the electron occupy any spatial point in between the two orbitals. But this is not what makes this event really queer. What makes a quantum leap unlike any other is that there is no determinate answer to the question of where and when they happen. The point is that it is the intra-play of continuity and discontinuity, determinacy and indeterminacy, possibility and impossibility that constitutes the differential spacetimematterings of the world. Or to put it another way, if the indeterminate nature of existence by its nature teeters on the cusp of stability and instability, of determinacy and indeterminacy, of possibility and impossibility, then the dynamic relationality between continuity and discontinuity is crucial to the open-ended becoming of the world which resists acausality as much as determinism.

As discussed earlier, agency is the space of possibilities opened up by the indeterminacies entailed in exclusions. And agency, in this account, is a much larger space of possibilities than that generally considered. The reworking of exclusions entails possibilities for (discontinuous) changes in the topology of the world's becoming. But not everything is possible at every moment. Interior and exterior, past, present, and future, are iteratively enfolded and reworked, but never eliminated (and never fixed). Intra-actions reconfigure the possibilities for change. In fact, intra-actions not only reconfigure spacetimematter but reconfigure what is possible. Ethicality is part of the fabric of the world; the call to respond and be responsible is part of what is. There is no spatial-temporal domain that is excluded from the ethicality of what matters. Questions of responsibility and accountability present themselves with every possibility; each moment is alive with different possibilities for the world's becoming and different reconfigurings of what may yet be possible.[87]

CONCLUSIONS

Scholars in feminist studies, science studies, cultural studies, and critical social theory are among those who struggle with the difficulty of coming to terms with the "weightiness" of the world. On the one hand, there is an expressed desire to recognize and reclaim matter and its kindred spirits (e.g., the body) exiled from (or swallowed up by) the familiar and comforting domains of culture, mind, and history, not simply to altruistically advocate on behalf of the subaltern but in the hopes of finding a way to account for our own finitude. Can we identify the limits and constraints, if not the grounds, of discourse-knowledge in its productivity? But despite its substance, in the end, according to many contemporary attempts at its salvation, it is not matter that reels in the unruliness of infinite possibilities; rather, it is the very existence of finitude that gets defined as matter. Caught once again looking at mirrors, it is either the face of transcendence or our own image. It is as if there are no alternative ways to conceptualize matter: the only options seem to be the naiveté of empiricism or the same old narcissistic bedtime stories.

I have proposed a posthumanist account of performativity that challenges the positioning of materiality as either a given or a mere effect of human agency. In an agential realist account, materiality is an active factor in processes of materialization. Nature is neither a passive surface awaiting the mark of culture nor the end product of cultural performances. The belief that nature is mute and immutable and that all prospects for significance and change reside in culture merely reinscribes the nature-culture dualism that feminists have actively contested. Nor, similarly, can a human-nonhuman distinction be hard-wired into any theory that claims to take account of matter in the fullness of its historiality. To presume a given distinction between humans and nonhumans is to cement and recirculate the nature-culture dualism into the foundations of feminist theory, foreclosing a genealogy of how nature and culture, human and nonhuman, are formed. Hence any performative account worth its salt would be ill advised to incorporate such anthropocentric values in its foundations.

A crucial part of the performative account that I have proposed is a rethinking of the notions of discursive practices and material phenomena and the relationship between them. In an agential realist account, discursive practices are not human-based activities but specific material (re)configurings of the world through which boundaries, properties, and meanings are differentially enacted. And matter is not a fixed essence; rather, matter is substance in its intra-active becoming—not a thing but a doing, a congealing of agency. Apparatuses are material (re)configurings or discursive practices that produce (and are part of) material phenomena in their becoming. Discursive practices and material phenomena do not stand in a relationship of externality to each other; the material and the discursive are mutually implicated in the dynamics of intra-activity. In an agential realist account, performativity is understood not as iterative citationality (Butler) but as *iterative intra-activity*. Intra-actions are agentive, and changes in the apparatuses of bodily production matter for ontological as well as epistemological and ethical reasons: different material-discursive practices produce different material configurings of the world, different difference/diffraction patterns; they do not merely produce different descriptions. Objectivity and agency are bound up with issues of responsibility and accountability. Accountability must be thought of in terms of what matters and what is excluded from mattering.

In an agential realist account of technoscientific practices, the knower does not stand in a relation of absolute externality to the natural world—there is no such exterior observational point.[88] The condition of possibility for objectivity is therefore not absolute exteriority but agential separability—exteriority within phenomena.[89] We are not outside observers of the world. Neither are we simply located at particular places *in* the world; rather, we are part *of* the world in its ongoing intra-activity. This is a point Niels Bohr tried to get at in his insistence that our epistemology must take account of the fact that we are a part of that nature we seek to understand. Unfortunately, however, Bohr cut short important posthumanist implications of this insight in his ultimately humanist understanding of the "we." Vicki Kirby eloquently articulates this important posthumanist point: "I'm trying to complicate the locatability of human identity as a here and now, an enclosed and finished product, a causal force upon Nature. Or even . . . as something within Nature. I don't want the human to be in Nature, as if Nature is a container. Identity is inherently unstable, differentiated, dispersed, and yet strangely coherent. If I say 'this is Nature itself,' an expression that usually denotes a prescriptive essentialism and that's why we avoid it, I've actually animated this 'itself' and even suggested that 'thinking' isn't the other of nature. Nature performs itself differently."[90]

The particular configuration that an apparatus takes is not an arbitrary construction of our choosing; nor is it the result of causally deterministic power structures. Humans do not simply assemble different apparatuses for satisfying particular knowledge projects but are themselves specific parts of the world's ongoing reconfiguring. To the degree that laboratory manipulations, observational interventions, concepts, and other human practices have a role to play, it is as part of the material configuration of the world in its intra-active becoming. Humans are part of the world-body space in its dynamic structuration.

There is an important sense in which practices of knowing cannot fully be claimed as human practices, not simply because we use nonhuman elements in our practices but because knowing is a matter of part of the world making itself intelligible to another part. Practices of knowing and being are not isolable; they are mutually implicated. We don't obtain knowledge by standing outside the world; we know because we are *of* the world. We are part of the world in its differential becoming. The separation of epistemology from ontology is a reverberation of a metaphysics that assumes an inherent difference between human and nonhuman, subject and object, mind and body, matter and discourse. *Onto-epistem-ology*—the study of practices of knowing in being—is probably a better way to think about the kind of understandings that we need to come to terms with how specific intra-actions matter. Or, for that matter, what we need is something like an *ethico-onto-epistem-ology*—an appreciation of the intertwining of ethics, knowing, and being—since each intra-action matters, since the possibilities for what the world may become call out in the pause that precedes each breath before a moment comes into being and the world is remade again, because the becoming of the world is a deeply ethical matter.

PART III
ENTANGLEMENTS AND RE(CON)FIGURATIONS

FIVE

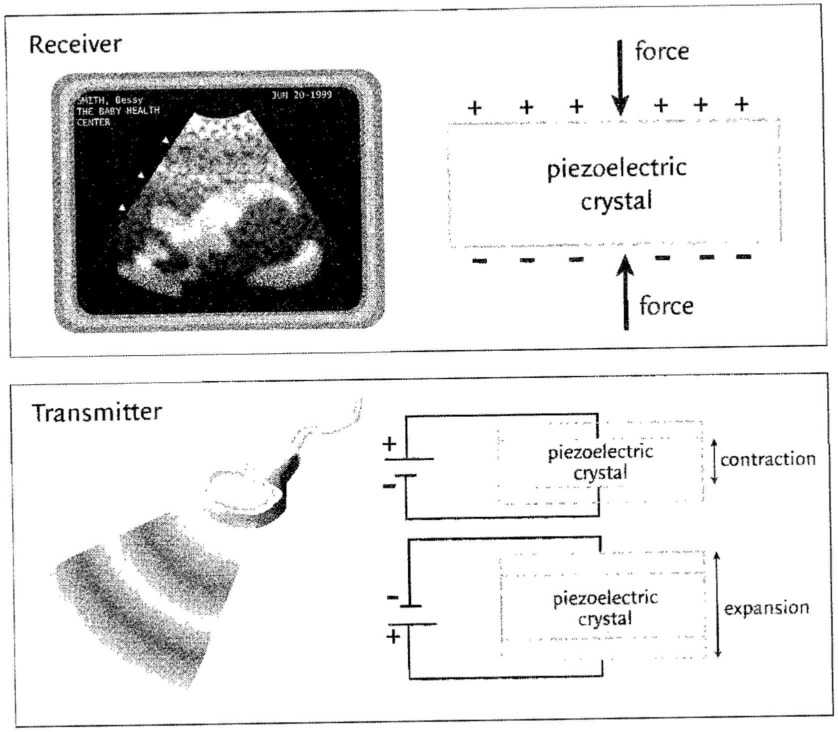
Getting Real: Technoscientific Practices and the Materialization of Reality

> The body is . . . directly involved in a political field; power relations have an immediate hold upon it; they invest it, mark it, train it, torture it, force it to carry out tasks, to perform ceremonies, to emit signs . . . power is not exercised simply as an obligation or prohibition on those who "do not have it"; it invests them, is transmitted by them and through them; it exerts pressure upon them, just as they themselves, in their struggle against it, resist the grip it has on them.
>
> —MICHEL FOUCAULT, *Discipline and Punish*

Power is transmitted through the repeated application of pressure on the body. The body reacts to the forces, manifest as shifting material alignments and changes in potential, and becomes not simply the receiver but also the transmitter or local source of the signal or sign that operates through it. It is this responsiveness of the body that makes it the effect and instrument of visualizing technologies.[1]

While Foucault's comments refer to the human body, my subject matter is a piezoelectric crystal. When pressure is applied to a piezoelectric crystal, it emits an electric signal that can be amplified and displayed visually (see figure 16, top diagram). Conversely, piezoelectric crystals undergo deformation in the presence of an electric field. More specifically, if an electric signal is applied to the crystal, it will expand or contract depending on the polarity of the signal (see figure 16, bottom diagram). High-frequency oscillating signals cause the crystal to vibrate, resulting in the propagation of ultrasonic waves. The piezoelectric effect was first observed by Pierre and Jacques Curie in 1880. Today the dual functionality of the piezoelectric crystal as both transmitter and receiver makes it the key element for a particularly poignant apparatus of observation—that of the transducer for ultrasonography.

In this chapter, I argue that the piezoelectric crystal is a material instrument, the "soul" of an observing apparatus, through which not simply



16 This diagram illustrates the dual function of the piezoelectric crystal, which operates as both a transmitter and a receiver of ultrasonic waves. The top diagram (the piezoelectric crystal acting as a receiver) shows what happens when ultrasonic waves impinge on the crystal (after they've reflected off their target): as a result of the piezoelectric effect, the force exerted by the ultrasonic waves on the crystal causes it to deform and emit an electrical signal. The pattern of the incoming ultrasonic waves varies with the target encountered, and the electric signal emitted by the piezoelectric crystal can be mapped onto a visual image and displayed on a computer screen. The bottom diagram (the piezoelectric crystal acting as a transmitter) shows how a piezoelectric crystal can be used to produce ultrasonic waves. The piezoelectric crystal is hooked up to a power source. Depending on the polarity of the power source, the crystal either expands or contracts. If a high-frequency alternating current source is used, the crystal responds by rapidly expanding and contracting. The rapid expansion and contraction produces high-frequency pressure waves, that is, ultrasonic waves. *Based on the drawing by Karen Barad (1998c, 88). Illustration by Nicolie Rager Fuller for the author.*

signals but discourses operate.[2] Examining the coupling of this instrument to an array of apparatuses, I use the piezoelectric transducer as a tool to explore the relationship between the material and the discursive. This relationship is at the center of the philosophical framework I call agential realism.

THE MATERIALIZATION OF BODIES

A text that has become canonical for its engagement with issues of subjectivity and the materiality of the body is Judith Butler's provocative book *Bodies That Matter: On the Discursive Limits of "Sex."* In this text, Butler offers an account of the subject that acknowledges the important constituting effects of discourse and power, without falling prey to social determinism. And she gives an account of the material nature of the human body without reinstalling the body's materiality as foundational or self-evident. Butler develops a notion of gender performativity that links subject formation to the production of the body's materiality.

Butler opens the book with a critique of the notions of construction that circulate in feminist theory and challenges feminists to "return to the notion of matter, not as a site or surface, but as a process" (9):

> To claim that sex is already gendered, already constructed, is not yet to explain in which way the "materiality" of sex is forcibly produced. What are the constraints by which bodies are materialized as "sexed," and how are we to understand the "matter" of sex, and of bodies more generally, as the repeated and violent circumscription of cultural intelligibility? Which bodies come to matter—and why? (xi–xii)

Butler's contention that matter should be understood as "a process of materialization that stabilizes over time to produce the effect of boundary, fixity, and surface" (9) is important in its reconsideration of what it could mean to claim that bodies are "socially constructed." However, Butler's notion of materialization is limited in several important ways. In this chapter, I examine some of these limitations and suggest an alternative understanding of materiality, discursivity, and performativity in the context of the practice of fetal ultrasonography.[3]

A question that goes to the heart of the matter is whether Butler's account of materialization is sufficient to take us beyond the passive-active, nature-culture dualisms that her displacement of construction is in part meant to counter. For as the subtitle "On the Discursive Limits of 'Sex'" already hints, while Butler's temporal account of materialization displaces matter as a fixed and permanently bounded entity, its temporality is analyzed only in terms of how *discourse* comes to matter.[4] Butler's account fails to analyze how *matter* comes to matter. What about the "material limits": the material constraints and exclusions, the material dimensions of agency, and the material dimensions of regulatory practices? Doesn't an account of materialization that is attentive only to discursive limits reinscribe this very dualism by implicitly reinstalling materiality in a passive role?

Since the questions I want to raise concern the way that matter is incorporated into Butler's account of materialization, I want to carefully distinguish my critique from a host of accusations against Butler that incorrectly accuse her of idealism, linguistic monism, or a neglect or even erasure of "real flesh-and-blood bodies." It would be a gross misunderstanding of Butler's work to accuse her of collapsing the complex issue of materiality to one of mere discourse, of arguing that bodies are formed from words, or of asserting that the only way to make the world a better place is through resignification. On the contrary, Butler *does* provide us with an insightful and powerful analysis of some *discursive* dimensions of the materialization of real flesh-and-blood bodies. My point is that the analysis of materialization that Butler offers leaves out critical components.

That Butler's analysis enacts its own exclusions is not in and of itself a fatal flaw. On the contrary, according to Butler's own treatment of the nature of exclusions, they are not only necessary but productive, particularly in their instability and consequent availability for rearticulation. An obvious question, though, is whether the redrawing of lines, the enactment of new cuts, to counter the passivity of materiality, entails a necessary renunciation of Butler's theory of performativity, or whether an enlarged account of materiality can be offered that can enact a productive appropriation and elaboration of her theory. That is, is the exclusion of particular features of materiality a constitutive constraint of analyzing materiality performatively? It is far from obvious how to take account of material constraints, for example, if materiality itself is the "dissimulated effect of power." Isn't some *fixed* sense of the substantive character of materiality required to think about how materiality constrains processes? And, furthermore, if it has taken this much work to wake us from our ontological illusions, does any reference to material constraints threaten to undercut this achievement?

TECHNOLOGIES OF EMBODIMENT

In the section of *Bodies That Matter* where Butler explains her conception of materialization, she offers an example of the medical interpellation of an infant at birth—or prior to the birth of a fetus through the use of ultrasound technology—which initiates the reiterative process of becoming a gendered subject:

> Consider the medical interpellation which (the recent emergence of the sonogram notwithstanding) shifts an infant from an "it" to a "she" or a "he," and in that naming, the girl is "girled," brought into the domain of language and kinship through the interpellation of gender. But that "girling" of the girl does not end there; on the contrary, that founding interpellation is reiterated by various authorities and throughout various intervals of time to reinforce or contest this naturalized effect. The naming is at once the setting of a boundary, and also the repeated inculcation of a norm. (7–8)

But is the parenthetical inclusion of gender interpellation through ultrasound technologies really so unremarkable, so insignificant to considerations of (interpellation and ultimately of) materialization, that it requires no further analysis? Can this potential oversight, this offhand dismissal of significant differences signaled by the phrase "notwithstanding," simply be rectified by adding the appropriate material constraints, or is it possible that the very accounting of discursive constraints may require revision once material constraints are brought into the analysis, that is, once there is a reworking of what is here excluded?

As feminist analyses have made clear, ultrasound technology is a historically and culturally specific practice, involving discursive and material elements, that has differential effects on different bodies and lives. As Alice Adams (1994) notes: "Representations of the mother-fetus relationship in medical illustrations must be read as channels of economic as well as informational and ideological exchange" (128). For example, beyond the obvious economic limitations of differential *access* to such technologies is the question of differential *impact* for those who do have access, and ultimately for those who do not. Dion Farquhar (1996) writes:

> Recent years have witnessed expanded attempts by some physicians, ethicists, and legal scholars to hold pregnant women liable for causing prenatal harm, to impose criminal or civil sanctions on them after the birth of a sick or disabled infant, to restrict the behaviors of pregnant women, and to impose

> medical or surgical procedures . . . forcibly on them, ostensibly in order to prevent fetal harm. These interventions treat the mother as a mere maternal environment relative to a rights-bearing fetus that is analogically compared to a pediatric case. The targeting of poor, relatively disenfranchised pregnant women of color who are drug abusers is clearly a wedge for moralist state regulation of all women's bodies in a symptomatic displacement of social amelioration from one of its principal sources—exacerbated conditions of racialized poverty. (170)

The material and discursive dimensions of ultrasonography vary in time and in space. The sonogram does not simply map the terrain of the body; it maps geopolitical, economic, and historical factors, as well. For example, Teresa Ebert (1996) warns that gender interpellation must be understood in terms of the relevant relations of production:

> This truth is painfully clear if we move beyond the privileged boundaries of the upper-middle class in the industrialized West . . . and see what is happening to "girling" in the international division of labor—especially among the impoverished classes in India. Here the "medical interpellation" . . . of . . . fetuses, particularly through the use of the sonogram, immediately places "girled" fetuses not only in discourse but also in the gender division of labor and unequal access to social resources. About 60 percent of the "girled" fetuses are being immediately aborted or murdered upon birth . . . because the families cannot afford to keep them. The citational acts, rituals, and "performatives" by which individuals are repeatedly "girled" . . . are not simply acts of discourse but economic practices. (360)

Feminist analyses of scientific and technological developments have made evident that there are material as well as discursive factors that are important to the process of materialization, and while Butler would surely not deny this, her analysis does not give us any insights into how to take account of the material constraints, the material dimensions of agency, and the material dimensions of regulatory practices that make the gender interpellation of the fetus through ultrasound technology different from a situation in which "girling" begins at birth.

BOHR'S EPISTEMOLOGICAL FRAMEWORK

Representationalism and Newtonian physics have roots in the seventeenth century.[5] The assumption that language is a transparent medium that transmits a homologous picture of reality to the knowing mind finds its parallel

in a scientific theory that takes observation to be the benign facilitator of discovery, a transparent and undistorting lens passively gazing at the world. Just as words provide descriptions—representations of reality—so observations reveal preexisting properties of an observation-independent reality. In the twentieth century, both the representational or mimetic status of language and the inconsequentiality of the observational process have been called into question.

I turn to the work of the physicist Niels Bohr as a place to begin articulating my notion of agential realism. Bohr's search for a coherent interpretation of quantum physics led him to more general epistemological considerations that challenged representationalist assumptions about the nature of scientific inquiry. Ultimately, Bohr proposed what is arguably understood as a proto-performative account of scientific practices. His early-twentieth-century epistemological investigations focused on issues of contemporary significance: (1) the connections between descriptive concepts and material apparatuses, (2) the inseparability of the "objects of observation" and the "agencies of observation," (3) the emergence and co-constitution of the objects of observation and the agencies of observation through particular material and conceptual epistemic practices, (4) the interdependence of material and conceptual constraints and exclusions, (5) the material conditions for objective knowledge, and (6) the reformulation of the notion of causality. Diffractively reading Bohr's and Butler's insights through one another for the patterns of resonance and dissonance they coproduce usefully illuminates the questions at hand.[6]

Bohr's careful analysis of the process of measurement led him to conclude that two implicit assumptions needed to support the Newtonian framework and its notion of the transparency of observations were flawed: (1) that the world is composed of individual objects with individually determinate boundaries and properties whose well-defined values can be represented by abstract universal concepts that have determinate meanings independent of the specifics of the experimental practice, and (2) that measurements involve continuous determinable interactions such that the values of the properties obtained can properly be assigned to the premeasurement properties of objects as separate from the agencies of observation. In other words, the assumptions entail a belief in representationalism (the independently determinate existence of words and things), the metaphysics of individualism (that the world is composed of individual entities with individually determinate boundaries and properties), and the intrinsic separability of knower and known (that measurements reveal the preexisting values of the properties of independently existing objects as separate from the measuring agencies).

In contrast to these Newtonian assumptions, Bohr argued that *theoretical concepts are defined by the circumstances required for their measurement.* That is, concepts are specific material arrangements.[7] It follows from this fact, and the fact that there is an empirically verifiable discontinuity in measurement interactions, that there is no unambiguous way to differentiate between the object and the agencies of observation. As no inherent cut exists between object and agencies of observation, measured values cannot be attributed to observation-independent objects. In fact, Bohr concluded that observation-independent objects do not possess well-defined inherent properties.[8]

Bohr constructs his post-Newtonian framework on the basis of "quantum wholeness" or inseparability, that is, the lack of an inherent distinction between the object and the agencies of observation. He uses the term "phenomenon," in a very specific sense, to designate particular instances of "wholeness": "While, within the scope of classical physics, the interaction between object and apparatus can be neglected or, if necessary, compensated for, in quantum physics *this interaction thus forms an inseparable part of the phenomenon*. Accordingly, the unambiguous account of proper quantum phenomena must, in principle, include a description of all relevant features of the experimental arrangement" (Bohr 1963c, 4; italics mine).[9]

Bohr's insight concerning the intertwining of the conceptual and physical dimensions of measurement processes is central to his epistemological framework. The physical apparatus marks the conceptual subject-object distinction: the physical and conceptual apparatuses form a nondualistic whole. That is, descriptive concepts obtain their meaning by reference to a particular physical apparatus, which in turn marks the placement of a constructed cut between the object and the agencies of observation. For example, instruments with fixed parts are required to understand what we mean by the concept "position." However, any such apparatus necessarily excludes other concepts, such as "momentum," from having meaning during this set of measurements, since these other variables require an instrument with movable parts for their definition. Physical and conceptual constraints and exclusions are co-constitutive.

Since there is no inherent cut delineating the object from the agencies of observation, the following question emerges: what sense, if any, should we attribute to the notion of observation? Bohr suggests that "by an experiment we simply understand an event about which we are able in an unambiguous way to state the conditions necessary for the reproduction of the phenomena."[10] This is possible on the condition that the experimenter introduces a constructed cut between an object and the agencies of observation.[11] That is, in contrast to the Newtonian worldview, Bohr argues that no inherent distinction preexists the measurement process, that every measurement involves a particular choice of apparatus, providing the conditions necessary to define a particular set of classical variables, to the exclusion of other equally essential variables, thereby embodying a particular constructed cut delineating the object from the agencies of observation. This particular constructed cut resolves the ambiguities only for a given context; it marks off, and is part of, a particular instance of wholeness (i.e., the phenomenon).

Especially in his later writings, Bohr insists that quantum mechanical measurements are "objective." Since he also emphasizes the inseparability of objects and agencies of observation, he cannot possibly mean by "objective" that measurements reveal inherent properties of independent objects. But Bohr does not reject objectivity out of hand; he reformulates it. For Bohr, objectivity is a matter of "permanent marks—such as a spot on a photographic plate, caused by the impact of an electron—left on the bodies which define the experimental conditions" (Bohr 1963c, 3). Objectivity is defined in reference to bodies, and as we have seen, reference must be made to bodies in order for concepts to have meaning. Clearly, Bohr's notion of objectivity, which is not predicated on an inherent distinction between objects and agencies of observation, stands in stark contrast to a Newtonian sense of objectivity as denoting observer independence.[12]

The question remains: what is the referent of any particular objective property? Since there is no inherent distinction between object and apparatus, the property in question cannot meaningfully be attributed to either an abstracted object or an abstracted measuring instrument. That is, the measured quantities in a given experiment are not values of properties that belong to an observation-independent object, nor are they purely artifactual values created by the act of measurement (which would belie any sensible meaning of the word "measurement"). My reading is that the *measured properties refer to phenomena*, remembering that phenomena are physical-conceptual (material-discursive) intra-actions whose unambiguous account requires "a description of all relevant features of the experimental arrangement." I introduce the neologism "intra-action" to signify *the mutual constitution of objects and agencies of observation within phenomena* (in contrast to "interaction," which assumes the prior existence of distinct entities). In particular, the different agencies ("distinct entities") remain entangled.[13]

While Newtonian physics is well known for its strict determinism, its widely acclaimed ability to predict and retrodict the full set of physical states of a system for all times, based on the simultaneous specification of two particular variables at any one instant, Bohr's general epistemological framework proposes a radical revision of such an understanding of causality.[14] He explains that the inseparability of the object from the apparatus "entails . . . the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality" (Bohr 1963b, 59–60). While claiming that his analysis forces him to renounce the classical ideal of causality, that is, of strict determinism, Bohr does not presume that this entails overarching disorder, lawlessness, or an outright rejection of the cause-and-effect relationship. Rather, he suggests that our understanding of the terms of that relationship must be reworked: "The feeling of volition and the demand for causality are equally indispensable elements in the relation between subject and object which forms the core of the problem of knowledge" (Bohr 1963a, 117). In short, he rejects both poles of the usual dualist thinking about causality—freedom and determinism—and proposes a third possibility.

Bohr's epistemological framework deviates in an important fashion from classical correspondence or mirroring theories of scientific knowledge. For example, consider the wave-particle duality paradox originating from early-twentieth-century observations conducted by experimenters who reported seemingly contradictory evidence about the nature of light: under certain experimental circumstances, light manifests particle-like properties, and under an experimentally incompatible set of circumstances, light manifests wavelike properties. This situation is paradoxical to the classical realist mind-set because the true ontological nature of light is in question: either light is a wave, or it is a particle; it cannot be both. Bohr resolved the wave-particle duality paradox as follows: "wave" and "particle" are classical descriptive concepts that refer to different mutually exclusive *phenomena*, not to independent physical objects. He emphasized that this saved quantum theory from inconsistencies, since it is impossible to observe particle and wave behaviors simultaneously because mutually exclusive experimental arrangements are required. To put the point in a more modern context, according to Bohr's general epistemological framework, referentiality must be reconceptualized: the referent is not an observation-independent object but a phenomenon. This shift in referentiality is a condition for the possibility of objective knowledge. That is, *a condition for objective knowledge is that the referent is a phenomenon* (and not an observation-independent object).

FROM IMAGING DEVICES TO MATERIALIZING PRACTICES

> Discipline "makes" individuals; it is the specific technique of a power that regards individuals both as objects and as instruments of its exercise. . . . The exercise of discipline presupposes a mechanism that coerces by means of observation; an apparatus in which the techniques that make it possible to see induce effects of power, and in which, conversely, the means of coercion make those on whom they are applied clearly visible.
>
> —MICHEL FOUCAULT, *Discipline and Punish*

Apparatuses, in Bohr's sense, are not passive observing instruments. On the contrary, they are productive of (and part of) phenomena. However, Bohr does not give a complete account of apparatuses. He does insist that what constitutes an "apparatus" emerges within specific observational practices. But while focusing on the lack of an inherent distinction between the apparatus and the object, Bohr does not directly address the question of where the apparatus "ends." In a sense, he establishes only the "inside" boundary, and not the "outside" one. For example, if a computer interface is hooked up to a given instrument, is the computer part of the apparatus? Is the printer attached to the computer part of the apparatus? Is the paper that is fed into the printer? Is the person who feeds the paper? How about the person who reads the marks on the paper? How about the community of scientists who judge the significance of the experiment and indicate their support or lack of support for future funding? What precisely constitutes the limits of the apparatus that gives meaning to certain concepts at the exclusion of others?

A central focus in Bohr's discussion of objectivity is the possibility of "unambiguous communication," which can only take place in reference to "bodies which define the experimental conditions" and embody particular concepts to the exclusion of others. This seems to indicate Bohr's recognition of the social nature of scientific practices: making meanings involves the interrelationship of complex discursive and material practices. What is needed is an articulation of the notion of apparatuses that acknowledges this complexity.[15]

Theorizing the social nature of knowledge practices is a challenge that is taken up by Michel Foucault. Like Bohr, Foucault is interested in the conditions for intelligibility and the productive and constraining dimension of practices embodied in "apparatuses." Reading Foucault's and Bohr's analyses of apparatuses through each other provides a richer overall account of apparatuses: it extends the domain of Bohr's analysis from the physical-conceptual to the material-discursive more generally; provides a further articulation of Foucault's theory, extending its domain to include the natural sciences and an account of the materialization of nonhuman as well as human bodies; takes seriously the epistemological and ontological inseparability of the apparatus from the objects and the subjects it helps to produce; and produces new understandings of materiality, discursivity, agency, causality, space, and time. Significantly, this diffractive reading produces a new understanding of how discursive practices are related to material phenomena.[16]

In *Discipline and Punish*, Foucault explains that the proliferation of what he variously calls "apparatuses of observation," "apparatuses of production," and "disciplinary apparatuses" is related to the eighteenth-century development of new technologies. Of particular noteworthiness is the panopticon as an observing instrument for the new human sciences and its role in the dispersion of power through the shaping and disciplining of docile bodies.[17] Through this technology of examination and individualization, this "political technology of the body," a new "microphysics of power" emerges: power evolves historically from acting as an external force on the individual to its more contemporary form, in which power is exercised through individual bodies. Disciplinary power orders the body, fixes and constrains movement. Foucault explains that "this technology is diffuse, rarely formulated in continuous, systematic discourse; it is often made up of bits and pieces; it implements a disparate set of tools or methods. In spite of the coherence of its results, it is generally no more than a multiform instrumentation" (Foucault 1977, 26). Disciplinary power is exercised through various apparatuses. It "link[s] them together, extending them and above all making it possible to bring the effects of power to the most minute and distant elements" (216).

Foucault's insights concerning disciplinary practices and the "microphysics of power" have profoundly altered the ways in which power and knowledge are currently theorized. However, there are crucial features of power-knowledge practices that Foucault does not articulate, including the precise nature of the relationship between discursive practices and material phenomena; a dynamic and agential conception of materiality that takes account of the materialization of all bodies (nonhuman as well as human and that makes possible a genealogy of the practices through which these distinctions are made); and the ways in which contemporary technoscientific practices provide for much more intimate, pervasive, and profound reconfigurings of bodies, power, knowledge, and their linkage than anticipated by Foucault's notion of biopower (which might have been adequate to eighteenth-century practices, but not contemporary ones).

I want to make a few comments on these points. Although Foucault insists that the objects (subjects) of knowledge do not preexist but emerge only within discursive practices, he does not explicitly analyze the inseparability of apparatuses and the objects (subjects). In other words, Foucault does not propose an analogue to the notion of phenomenon or analyze its important (ontological as well as epistemological) consequences. Does this insight contribute anything important to our understanding of material-discursive practices and the "microphysics of power?" And what about the nature of power and its dynamics in the twentieth and twenty-first centuries?[18] As Donna Haraway emphasizes in *Modest—Witness*, technoscientific practices are less involved in "dramas of health, degeneration, and the organic efficiencies and pathologies of production and reproduction" than the implosions of "the technical, organic, political, economic, oneiric, and textual" (Haraway 1997, 12). Haraway labels this latter mutated time-space regime "technobiopower," in contrast to the developmental sense of temporality that characterizes Foucault's "biopower."

In this spirit it is significant that while the panopticon may be exemplary of observing technologies in the eighteenth century, ultrasound technology makes for a particularly poignant contemporary apparatus of observation, and it is from this vantage point that I want to examine some of these issues. Significantly, in obstetric ultrasonography, the piezoelectric transducer is a prosthetic device for making and remaking boundaries (including those between nature and culture, human and nonhuman, living and nonliving, visible and invisible, autonomous and independent, self and other, as well as implosions and other reconfigurations of space and time). And it serves here as well as the interface (intra-face) for the reading of Bohr's and Foucault's insights through one another.

Ultrasonic waves were originally used for sound navigation and ranging (SONAR) in the detection of submarines during World War I. Further developments of sonar technologies during World War II led to important progress that facilitated their use in the field of medicine. Obstetric applications of ultrasound technology occurred in the late 1950s. By the mid-1960s, obstetric ultrasound gained wide acceptance in the medical community. A decade later, ultrasound was regarded as integral to the practice of obstetrics.

It is now common to find fetal ultrasound images immediately preceding pictures of newborns in family photo albums. But neither the production nor the interpretation of ultrasound images is a simple matter: both involve highly specialized forms of knowledge. In fact, the frequency of misdiagnosis using ultrasound technology is significant even with physician use, and the medical community is currently debating the possibility of mandatory certification for those using the technology. A textbook on ultrasonography states:

> Individuals admitted for training . . . should have post-secondary education in the following areas: medical ethics, medical terminology, clinical anatomy and physiology, medical orientations and administration, nursing procedures, general human anatomy, and elementary physics. . . . An ability to improvise the standard procedure when necessary is essential. . . . The ability to deviate from normal techniques when necessary and to develop new and better techniques to keep the department up to date is also the responsibility of the sonographer and the physician. (Hagen-Ansert 1983, 618)

The piezoelectric transducer is, in one account, the machine interface to the body. The transducer is both the source and the receiver of ultrasound waves. When sound waves reflected from different body parts impinge on the transducer, they are converted into electric signals that are visually displayed. A multitude of factors influence the image produced on the screen. Different kinds of tissue have different acoustic impedances; the reflection of the beam varies with the interface geometry, and with the differences in impedances between the materials making up an interface. Furthermore, the beam resolution is a function of the frequency, and different applications require different transducers. Each piezoelectric transducer has a natural resonant frequency that depends on the sample thickness and the mounting of the transducer element in the assembly, among other factors. Producing a "good" ultrasound image is not as simple as snapping a picture; neither is reading one.[19]

Employing a Bohrian epistemology makes the limitations of a conception of the piezoelectric transducer as a component of an idealized observing instrument evident: the transducer does not allow us to peer innocently at the fetus, nor does it simply offer constraints on what we can see; rather, it helps produce and is part of the body it images. That is, the marks on the computer screen (the sonogram images, sonic diffraction patterns translated into an electronic image) refer to a *phenomenon* that is constituted in the intra-action of the "object" (commonly referred to as the "fetus") and the "agencies of observation." Significantly, the objective referent for the properties that are observed is the *phenomenon, not* some presumably preexisting, determinately bounded and propertied object. (It could prove quite useful to contest and interrogate the common usage of the term "fetus" to refer to the object being imaged, since this is not the objective referent. Which referent

is assigned particular attributes matters for political and scientific reasons, for epistemology as well as ontology. Mistaking the object of observation for the objective referent can be used to certain political advantages, which may then have consequences for how scientific practices, among others, are reiterated. What if the term "fetus" is resignified to refer to the *phenomenon* in question?)

However, to understand the complex nature of the phenomenon in question, it is necessary to understand the nature of apparatuses and the processes by which they are produced. It would be wrong, for example, to equate the apparatus with the transducer and to conceive of the transducer as some preformed object that sits on a shelf and is available to whomever whenever it is needed. Apparatuses are not preexisting or fixed entities; they are themselves constituted through particular practices that are perpetually open to rearrangements, rearticulations, and other reworkings. This is part of the creativity and difficulty of doing science: getting the instrumentation to work in a particular way for a particular purpose (which is always open to the possibility of being changed during the experiment as different insights are gained).[20] Furthermore, any particular apparatus is always in the process of intra-acting with other apparatuses, and the enfolding of phenomena (which may be traded across space, time, and subcultures only to find themselves differently materializing) into subsequent iterations of particular situated practices constitutes important shifts in the particular apparatus in question, and therefore in the nature of the intra-actions that result in the production of new phenomena, and so on.[21] Which shifts actually occur matter for epistemological as well as ontological reasons. We are responsible for the world within which we live, not because it is an arbitrary construction of our choosing, but because it is sedimented out of particular practices that we have a role in shaping (see the section titled "On Agency and Causality" later in the chapter).[22] The materialization of an apparatus is an open (but nonarbitrary) temporal process: apparatuses do not simply change in time; they materialize (through) time. *Apparatuses are themselves material-discursive phenomena, materializing in intra-action with other material-discursive apparatuses.*[23]

For example, piezoelectric transducers materialize (and are iteratively rematerialized) in intra-action with a multitude of practices, including those that involve medical needs; design constraints (including legal, economic, biomedical, physics, and engineering ones); market factors; political issues; other R & D projects using similar materials; the educational background of the engineers and scientists designing the crystals and the workplace environment of the engineering firm or lab; particular hospital or clinic environments where the technology is used; receptivity of the medical community and the patient community to the technology; legal, economic, cultural, religious, political, and spatial constraints on its uses; positioning of patients during examination; and the nature of training of technicians and physicians who use the technology.[24] Hence the production and re-production of the technology involves particular disciplinary practices that Foucault specifically mentions such as those involving legal, educational, hospital, medical, architectural, military, industrial, and state apparatuses, and much more. The surveillance of technicians, physicians, engineers, and scientists in their formation as particular kinds of subjects is implicated in the surveillance of the fetus and vice versa. In obstetric ultrasonography, the piezoelectric transducer is the interface between the objectification of the fetus and subjectivation of the technician, physician, engineer, and scientist.[25]

Obstetric ultrasonography is not a singular practice but a range of different local practices involving a myriad of material configurations and discursive formations. For Foucault, apparatuses of observation are material arrangements that support particular discourses, where "discourses" are not merely "groups of signs" but "practices that systematically form the objects of which they speak" (Foucault 1972, 49). As we have seen, Bohr's insistence on the indissociability of materiality and intelligibility is central to his epistemological analysis and suggests an intimacy between their coupling that goes beyond Foucault's specification (or lack thereof).[26] Furthermore, using Foucault's theoretically sophisticated notion of discursivity to further articulate Bohr's narrow focus on linguistic concepts seems particularly apt.

On the other hand, Foucault's notion of materiality is not sufficiently developed to carry through this elaboration.[27] While Foucault analyzes the materialization of human bodies, he seems to take nonhuman bodies as naturally given objects. That is, Foucault does not consider the processes of materialization through which nonhuman bodies are materialized (nor does he concern himself with boundary-drawing practices through which the division between human and nonhuman is constituted). The mechanism of materialization offered by Foucault operates through the "soul," which he reads as a "certain technology of power over the body" (1977, 29).[28] In the next section, I offer a more general account of materiality and materialization, moving toward a crucial shift in Bohr's analysis from the physical-conceptual to the material-discursive.

HOW MATTER COMES TO MATTER

While talk about the "real" at the beginning of the twenty-first century may be the source of such discomfort that it always needs to be toned down, softened by the requisite quotation marks, I believe that "we" cannot afford not to talk about "it." Positivism's death warrant has many signatories, but its anti-metaphysics legacy lives on even in the heart of its detractors. However strong one's dislike of metaphysics, it cannot be banished, and so it is ignored at one's peril. How *reality* is understood matters. There are risks entailed in putting forward an ontology: making metaphysical assumptions explicit exposes the exclusions on which any given conception of reality is based. But the political potential of deconstructive analysis lies not in simply recognizing the inevitability of exclusions but in insisting on accountability for the particular exclusions that are enacted and in taking up the responsibility to perpetually contest and rework the boundaries. In this section, I propose an understanding of reality that takes account of the exclusions on which it depends and its openness to future reworkings.

Bohr's attitude toward the relationship between language and reality is exemplified by the following:

> Traditional philosophy has accustomed us to regard language as something secondary, and reality as something primary. Bohr considered this attitude toward the relation between language and reality inappropriate. When one said to him that it cannot be language which is fundamental, but that it must be reality which, so to speak, lies beneath language, and of which language is a picture, he would reply, "We are suspended in language in such a way that we cannot say what is up and what is down. The word 'reality' is also a word, a word which we must learn to use correctly." (Petersen 1985, 302)[29]

Unfortunately Bohr is not explicit about how he thinks we should use the word "reality." I argue that a consistent Bohrian ontology takes phenomena as the referent for "reality."[30] Reality is composed not of things-in-themselves, or of things-behind-phenomena, but of things-in-phenomena. Because phenomena constitute a nondualistic whole, it makes no sense to talk about independently existing things as somehow behind or as the causes of phenomena.

The ontology I propose does not posit some fixed notion of being that is prior to signification (as the classical realist assumes), but neither is being completely inaccessible to language (as in Kantian transcendentalism), nor completely of language (as in linguistic monism). In my agential realist account, *phenomena are constitutive of reality*. Crucially, in my elaboration and extension of Bohr's philosophy-physics from observational instruments as physical-conceptual devices to the more general notion of apparatuses as material-discursive practices, I also significantly rework the notion of phenomenon.[31] According to the framework of agential realism, *phenomena are the ontological inseparability of intra-acting agencies*. Importantly, I argue that phenomena are not the mere result of laboratory exercises engineered by human subjects but *differential patterns of mattering* ("diffraction patterns") produced through complex agential intra-actions of multiple material-discursive practices or apparatuses of bodily production, where *apparatuses are not mere observing instruments but boundary-drawing practices —specific material (re)configurings of the world—which come to matter*.

Material-discursive apparatuses are themselves phenomena made up of specific intra-actions, including those among humans and nonhumans, where the differential constitution of the human and the nonhuman designates particular phenomena, which are enfolded and reworked in the ongoing reconfiguring of apparatuses and the reconstitution of boundaries, and what gets defined as an object (or subject) and what gets defined as an apparatus are intra-actively constituted through specific practices.[32]

Reality is therefore not a fixed essence. *Reality is an ongoing dynamic of intra-activity*. To assert that reality is made up of phenomena is not to invoke one or another form of idealism. On the contrary, phenomena are specific material configurations of the world.[33] Phenomena are not mere human or social constructions (and they are surely not mere constructs); we don't simply make the world in our image. Human practices are not the only practices that come to matter, but neither is the world (at least as it currently exists) independent of human practices. The question is what role human practices play. In my agential realist account, humans do not merely assemble different apparatuses for satisfying particular knowledge projects; humans are part of the configuration or ongoing reconfiguring of the world—that is, they/we too are phenomena. In other words, humans (like other parts of nature) are *of* the world, not *in* the world, and surely not outside of it looking in. Humans are intra-actively (re)constituted as part of the world's becoming. Which is not to say that humans are the mere effect, but neither are they/we the sole cause, of the world's becoming. The particular configuration that an apparatus takes is not an arbitrary construction of our choosing; nor is it the result of causally deterministic power structures. To the degree that laboratory manipulations, observational interventions, concepts, and other human practices have a role to play, it is as part of the material

configuration of the world in its intra-active becoming. Human practices are agentive participants in the world's intra-active becoming. Phenomena are sedimented out of the process of the world's ongoing articulation through which part of the world makes itself intelligible to some other part.[34] Therefore we are responsible not only for the knowledge that we seek but, in part, for what exists.

Shifting our understanding of the ontologically real from that "which stands outside the sphere of cultural influence and historical change" (Fuss 1989, 3) to an agential realist ontology opens up a space for a new formulation of realism (and truth) that is not premised on a metaphysics of essence or the representational nature of knowledge. If the discursive practices by which we seek to describe phenomena do not refer to properties of abstract objects or observation-independent beings but rather actively reconfigure the world in its becoming, then what is being described by our epistemic practices is not nature itself but *our intra-activity as part of nature*. That is, realism is reformulated in terms of the goal of providing accurate descriptions of that reality of which we are a part and with which we intra-act, rather than some imagined and idealized human-independent reality. Not all practices are equally efficacious partners in the production of phenomena, that is, in the iterative processes of materialization (simply saying something is so will not cause its materialization); and explanations of various phenomena and events that do not take account of material, as well as discursive, constraints will fail to provide empirically adequate accounts (not any story will do).[35] I use the label *agential realism* for both the new form of realism and the larger epistemological and ontological framework that I propose.

If technoscientific practices play a role in producing the very phenomena they set out to describe, might not this process be understood in a performative sense? Does the framework of agential realism provide a way for us to understand the materialization of bodies in terms of the intra-active production of phenomena? And if so, doesn't this imply that material constraints and exclusions and the material dimension of regulatory practices are important to the process of materialization, that performativity must be understood as not simply an issue of how discourse comes to matter but also of how matter comes to matter?

Several challenges arise in exploring the possibility of understanding technoscientific practices in terms of Butler's theory of performativity. Perhaps the most immediate question is whether Butler's notion of materialization is robust enough to extend her theory to considerations beyond the realm of the human body. Feminists have already questioned whether Butler's notion of materialization is robust enough for its own purposes: Does it adequately account for the processes by which human bodies materialize as sexed? What insights might be gained from science and science studies that could productively be appropriated in the further articulation of feminist theories? Could a physicist's understanding of matter and scientific practices usefully intervene in feminist reconceptualizations of materiality, so that it becomes possible to understand not only how bodily contours are constituted through psychic processes, but how even the very atoms that make up the biological body come to matter, and more generally how matter makes itself felt? Is it possible that such a revised account of performativity could lead us to a realist understanding of the materialization of bodies, one that takes full account of materiality and yet does not reinstall it as a site, or a surface, or a natural uncontested ground or bedrock for feminist theory?

Reading agential realism and Butler's theory of performativity through each other is not about some proclaimed symmetry between subject and object, or social and scientific practices, but rather about the production of mutually informative insights that might be useful in producing an enriched understanding of materiality, agency, and the nature of technoscientific and other social processes.[36] I argue in what follows that an agential realist reconceptualization of agency, causality, and materiality suggests a reworking of Butler's notion of performativity from iterative citationality to iterative intra-activity. I begin with a brief review of some key claims of agential realism.

In the previous section, I argued that apparatuses are iteratively produced or reconfigured in intra-action with other apparatuses—that apparatuses are themselves material-discursive phenomena. Since material-discursive apparatuses intra-actively produce material-discursive phenomena, the temporality of apparatuses is implicated (with)in and as part of an ever-changing agential reality. Phenomena are the effect of boundary-drawing practices that make some identities or attributes intelligible (determinate) to the exclusion of others. The identities or attributes that are determinate do not represent inherent properties of subjects or objects. Subjects and objects do not preexist as such but are constituted through, within, and as part of particular practices. The objective referents for identities or attributes are the phenomena constituted through the intra-action of multiple apparatuses. Phenomena are inseparable from their apparatuses of bodily production. Hence, according to agential realism, materialization needs to be understood in terms of the dynamics of intra-activity.

Butler's statement that at stake in her reformulation of the materiality of bodies is "the recasting of the matter of bodies as the effect of a dynamic of power, such that the matter of bodies will be indissociable from the regulatory norms that govern their materialization and the signification of those material effects" (1993, 2) might be read in agential realist terms as a statement of the effect that bodies are material-discursive phenomena that materialize in intra-action with (and, by definition, are indissociable from) the particular apparatuses of bodily production through which they come to matter (in both senses of the word). However, although both Butler's theory of performativity and the framework of agential realism retheorize materiality as a process of materialization, they also differ in significant ways.

Butler's account of materiality raises a series of pressing questions. Granting, for the moment, an account of the nature of the human body such that, through the mechanism of psychic identification, it remains perpetually vulnerable to the workings of social norms, is there a way to account for the ability of these norms to materialize the very substance of the human body? That is, what is it about the material nature of regulatory practices and of human bodies that enables discourse to work its productive material effects on bodies? If regulatory practices are understood to have a material dimension, how is that materiality theorized? Is the materiality of regulatory apparatuses different somehow from the materiality of the human body? What is the relationship between materiality and discourse such that regulatory apparatuses are susceptible to being reworked through resignifications as well as through material rearrangements?

Perhaps the most crucial limitation of Butler's theory of materiality is that it is limited to an account of the materialization of human bodies (or, more accurately, to the construction of the surface of the human body, which most certainly is not all there is to human bodies) through the regulatory action of social forces (which are not the only forces relevant to the production of bodies). The importance of Butler's contribution should not be underestimated. Understanding the psychic dimension of regulatory practices is a crucial component of understanding how bodies come to matter and how the process of their materialization enables critical interventions into the very process that reworks the terms of exclusion and production.

In contrast to Butler's more singular focus on the human body and social forces, crucially, the framework of agential realism does not limit its reassessment of the matter of bodies to the realm of the human (or to the body's surface) or to the domain of the social. In fact, it calls for a critical examination of the practices by which the differential boundaries of the human and the nonhuman, and the social and the natural, are drawn, for these very practices are always already implicated in particular materializations.[37] In my agential realist account, matter as a process of materialization is theorized beyond the realm of the human and the social, providing a more complete and complex understanding of the nature of practices (including regulatory ones) and their participatory role in the production of bodies. *Matter is substance in its intra-active becoming—not a thing, but a doing, a congealing of agency. Matter is a stabilizing and destabilizing process of iterative intra-activity.* Phenomena come to matter through this process of ongoing intra-activity. That is, *matter refers to the materiality and materialization of phenomena*, not to an assumed, inherent, fixed property of abstract, independently existing objects.

Significantly, this account applies to power/knowledge practices (Foucault); however, power is not restricted to the domain of the social but is rethought in terms of its materializing potential. That is, power operates through the enactment of natural as well as social (indeed naturalsocial forces) and the productive nature of regulatory practices is to be understood more generally in terms of causal intra-actions. I discuss causality later in the chapter, but a sense of what is at issue here can be gained by considering the nature of the materiality of regulatory practices. To put it bluntly, if not crudely, the material dimension of regulatory apparatuses, which is indissociable from their discursive dimension, is to be understood in terms of the materiality of phenomena. Apparatuses have a physical presence or an ontological thereness as phenomena in the process of becoming; there is no fixed metaphysical outside. This framework provides a way to understand both the temporality of regulatory practices and their effectiveness (and lack thereof) in intra-actively producing particular bodies that also have a physical presence. In essence, agential realism theorizes the material dimension of regulatory apparatuses in terms of the materiality of phenomena; it thereby provides an account of regulatory (and other) practices and their causal (but nondeterministic) materializing effects in the intra-active production of material-discursive bodies.[38] Hence materialization is a matter not only of how discourse comes to matter but of how matter comes to matter. Or to put it more precisely, *materialization is an iteratively intra-active process of mattering whereby phenomena (bodies) are sedimented out and actively re(con)figured through the intra-action of multiple material-discursive apparatuses. Matter is a stabilizing and destabilizing process of iterative intra-activity.*

Notice that there is a difference between the material instantiation of language in bodily gestures, or in sound waves propagating through the air, or in measuring devices: matter matters, and so the nature of the specific embodiment matters. Also, there is no guarantee that any of these embodied

actions will be efficacious. Intra-actions are not causally deterministic. Saying something is so does not make it so. Likewise, making and using particular instruments in a lab do not produce whatever results are desired.

Butler assigns different kinds of materialities to different discursive practices: "It must be possible to concede and affirm an array of 'materialities' that pertain to the body, that which is signified by the domains of biology, anatomy, physiology, hormonal and chemical composition, illness, age, weight, metabolism, life and death. None of this can be denied" (1993, 66). But the assertion of different kinds presumes separate discursive domains. In my agential realist account, there is important reason to suspect that these different discursive practices are not separate at all but entangled in specific ways; that is, these apparatuses of bodily production do not act in isolation from one another but rather engage in mutual intra-actions "with" one another. It is important not to start with reified distinctions from the outset but to do the necessary genealogical analyses to see what the specific material configurations look like. Agential realism circumvents the problem of different materialities: there is no need to postulate different materialities (i.e., materialities that are inherently of different kinds), and so there is no mystery about how the materiality of language could ever possibly affect the materiality of the body. According to agential realism, there aren't separate kinds of materiality and so the linkage between discursive practices and their materializing effects on bodies is not at all mysterious; discursive practices are materially efficacious, to the extent that they are, because there is a *causal* linkage between them, which is to be understood in terms of the causality of intra-actions (see the discussion later in this chapter).

The power of refiguring materiality as materialization is diluted if we limit its role to being merely an effect of the reiterative power of discourses or a mere support for language. The agential realist ontology offered here also makes it possible to take account of the material dimensions of agency and the material dimensions of constraints and exclusions without presuming matter to be a fixed ground existing outside of time, history, or culture. *Reference to the material constraints and exclusions and the material dimensions of power is possible within the framework of agential realism because "materiality" refers to phenomena, which are explicitly not elements of nature-outside-of-culture.* Any attempt to reinstate materiality as "natural"—as brute positivity or the essential givenness of things—would be exposed as being quite bizarre, since this would be to assign materiality to a place outside the real (i.e., it would be to lose track of the objective referent).[39]

Significantly, taking full account of the nature of material-discursive constraints and exclusions is important for understanding the materialization of bodies as well as the nature of abjection. Since the material and the discursive are intra-twined in apparatuses of bodily production, material and discursive constraints operate through one another (the same is true for exclusions), and hence a full consideration of the limits to materialization needs to include an analysis of both dimensions in their relationship to each other, that is, as material-discursive constraints (exclusions).

For example, according to agential realism, in spite of ultrasonography's origins in sonar technology developed during World War I, ultrasonography is not an idealized surveillance technology, a merely physical instrument that provides a view of the fetus as it exists independently of observational apparatuses. Rather, ultrasound technology designates specific material-discursive practices, constraining and enabling what is seen and produced in accordance with its iteratively intra-active technoscientific, medical, economic, political, biological, and cultural development as an ever-changing phenomenon, and by its related and particular usages as a material-discursive apparatus of bodily production in intra-action with other historically and culturally specific apparatuses. So, for example, technological improvements in fetal imaging, particularly material concerns such as increased resolution, magnification, and real-time images, encourage the patient and the practitioner to focus exclusively on the fetus, whose moving image fills the entire screen. Such material rearrangements both facilitate and are in part conditioned by political discourses insisting on the autonomy and subjectivity of the fetus.[40] This has been accompanied by the objectification of the pregnant woman and the exclusion of her subjectivity. Material-discursive constraints and exclusions are inseparable—a fact that we cannot afford to ignore.

ON AGENCY AND CAUSALITY

> Coming to terms with the agency of the "objects" studied is the only way to avoid gross error and false knowledge of many kinds in [the social and human] sciences. But the same point must apply to the other knowledge projects called sciences. . . . The world neither speaks itself nor disappears in favour of a master decoder. The codes of the world are not still, waiting only to be read. . . . Acknowledging the agency of the world in knowledge makes room for some unsettling possibilities, including a sense of the world's independent sense of humour. Such a sense of humour is not comfortable for humanists and others committed to the world as a resource.
>
> —DONNA HARAWAY, *Simians, Cyborgs, and Women*

> Nonhuman agency deflects attention from human accountability to other entities, whether human, nonhuman, cyborg, or what/whomever.
>
> —MONICA CASPER, "Reframing and Grounding Nonhuman Agency"

Foucault's theory of power is not deterministic. The subject is not determined by power relations; rather, subject formation may involve conflict, struggles, and local acts of resistance. How are such resistances possible? Butler takes up this question by examining how causality figures in Foucault's microphysics of power, and she then offers her own account of agency based on her theory of performativity. I begin this section with a brief review of Butler's account of causality and agency. I then address the question of causality from the perspective of agential realism and examine the implications for an enlarged account of agency.

If, according to Foucault, power is not simply constraining but also productive, if it does not act as an external force on a subject but rather operates through the very constitution of the subject, then how is it possible to even begin to address the issue of causality? And yet this issue is of great significance, for what is at stake in the notion of causality is both the question of agency and the meaning of construction.[41]

Butler understands materialization "in relation to the productive and . . . materializing effects of regulatory power in the Foucaultian sense" (1993, 9–10). In fact, she takes the materialization of the body to be coextensive with the body's investiture with power relations. Butler sees this understanding of the materialization of the body, through the productive workings of power, as an occasion for rethinking causality. Hence, when she writes that " 'materiality' designates a certain effect of power" (1993, 34), she cautions that "this is not to make 'materiality' into the effect of a 'discourse' which is its cause; rather, it is to displace the causal relation through a reworking of the notion of 'effect.' . . . The production of material effects is the formative or constitutive workings of power, a production that cannot be construed as a unilateral movement from cause to effect" (1993, 251).

In a performative context, the subject cannot be presumed to be the site of agency, since the subject does not have "some stable existence prior to the cultural field that it negotiates" (Butler 1990, 142). Rather, it is the reiterative character of performativity that opens up the possibility of agency: "That this reiteration is necessary is a sign that materialization is never quite complete, that bodies never quite comply with the norms by which their materialization is impelled" (1993, 2). Butler explains that the juncture of contradictory discursive demands on the subject prevents the subject from following them in strict obedience. "It is the space of this ambivalence which opens up the possibility of a reworking of the very terms by which subjectivation proceeds —and fails to proceed" (1993, 124). Hence, although norms are compulsory, this does not make them entirely efficacious, and the fact that the norm is never finally embodied but is always part of a citational chain presents an opportunity for a subversive resignification of the norm.

How are the issues of causality and agency formulated in the context of agential realism? Bohr insists that his analysis shows that causality is neither a matter of strict determinism nor one of unconstrained freedom. Causes are not forces that act on the phenomenon from outside. Nor should causes be construed as a unilateral movement from cause to effect. Rather, the "causes" and "effects" emerge through intra-actions. In particular, the "marks" left on the "agencies of observation" ("the effect") are said to constitute a measurement of specific features of the "object" ("the cause"). Furthermore, intra-actions always entail particular exclusions, and exclusions foreclose the possibility of determinism, providing the condition of an open future. The notion of intra-actions reformulates the traditional notion of causality and opens up a space for agency. Hence, according to agential realism, the possibility of agency does not require a "clash" of apparatuses (i.e., a set of contradictory cultural demands); even when apparatuses are primarily reinforcing, agency is not foreclosed.

Agency is a matter of intra-acting; it is an enactment, not something that someone or something has. Agency cannot be designated as an attribute of subjects or objects (as they do not preexist as such). Agency is a matter of making iterative changes to particular practices through the dynamics of intra-activity (including enfoldings and other topological reconfigurings). Agency is about the possibilities and accountability entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by those practices.[42]

What about the possibility of nonhuman forms of agency?[43] From a humanist perspective, the question of nonhuman agency may seem a bit queer, since agency is generally associated with issues of subjectivity and intentionality. However, if agency is understood as an enactment and not something someone has, then it seems not only appropriate but important to consider agency as distributed over nonhuman as well as human forms. This is perhaps most evident in considering fields such as science, where the subject matter is often "nonhuman." For as surely as social factors play a role in scientific knowledge construction (they are not the sole determinant—

things don't just come out any way we'd like them to), there is a sense in which "the world kicks back."

In a special issue of the journal *American Behavioral Scientist* entitled "Humans and Others: The Concept of 'Agency' and Its Attribution," Monica Casper (1994) offers a politically astute critique of the debates on nonhuman agency within science studies. She argues, for example, that actor network theorists, in their principled attribution of agency to humans and nonhumans, have failed to consider how the very notion of nonhuman agency is premised on "a dichotomous ontological positioning in which [nonhuman] is opposed to human" (840). She points out that their approach to nonhuman agency excludes a crucial factor from analysis, since "the *attribution* of human and nonhuman to heterogeneous entities" is always already the consequence of particular political practices. Casper demonstrates the kinds of political assumptions that can lie hidden in accounts that take for granted a preexisting distinction between humans and nonhumans by using her research on experimental fetal surgery to examine the construction of the "human" through particular technoscientific practices.

Casper argues that "a major way in which fetal personhood is accomplished . . . is via constructions of the fetus as a patient" (843):

> Through a range of practices within the domain of experimental fetal surgery, the fetus is constructed as a potential person with human qualities. In weekly fetal-treatment meetings, for example, fetuses are routinely referred to as "the kid," "the baby," and "he"—all quite human (and gendered) attributions. This process is aided by the use of diagnostic ultrasound which provides "baby pictures of fetuses still in their mothers' wombs" (Petchesky 1987; Stabile 1992). These images are used in fetal-treatment meetings during case presentations and are referred to in humanistic terms. (Casper 1994, 843)

She warns that "constructions of active fetal agency may render pregnant women invisible as human actors and reduce them to technomaternal environments for fetal patients" (844). Ultimately Casper draws the line in a seemingly ad hoc fashion: "I want historically 'nonhuman' people and animals to have agency (and I must admit I worry less about machines in this regard), but I do not necessarily want fetuses to have agency" (852). She justifies this move as follows: "My refusal to grant agency to fetuses, while simultaneously recognizing it in pregnant women and in my cats, is about taking sides. My politics . . . are about figuring out to whom and what in the world I am accountable" (853).

I strongly agree with Casper's point that it is a mistake to presume an a priori distinction between humans and nonhumans and foreclose the drawing of boundaries between the human and the nonhuman from critical analysis. But I am not so sanguine about the implicit universality of the boundary that she draws in her articulation of who or what gets to be an agent. Furthermore, Casper seems to imply that one is accountable only to that which one takes to be an agent. In light of this particular association of agency and accountability, what does it mean to forever exclude the consideration of fetal agency? Isn't it possible that in certain circumstances there may be a need empirically and strategically to invoke fetal agency to counter the material effects of sexism or other forms of oppression? For example, what are the implications of this exclusion in the case where "girled" fetuses in India are "aborted or murdered upon birth . . . because the families cannot afford to keep them" (Ebert 1996, 360)? The intensification of global neocolonialism, and the asymmetrical exclusions and constraints (such as those governed by asymmetrical flows of labor, capital, technology, and information) that accompany it, require ever more vigilance concerning questions of accountability, not less. The advanced foreclosure of agency may impair, or even completely occlude, the analysis of accountability that is so vitally important. The attribution and exclusion of agency—like the attributions and exclusions involved in the construction of the human—are a political issue.

Is the attribution of agency to the fetus a universal culprit? Where would particular kinds of feminist interventions, such as midwifery as an alternative to (over)medicalized birthing practices, be without acknowledging the fact that the fetus "kicks back"? I suggest that the critical issue lies not in the attribution of agency to the fetus in and of itself, but in the framing of the referent of the attribution (and ultimately in the framing of agency as a localizable attribution). As a starting point, I consider the following question: who or what is this "fetus" to which agency is being attributed?

The construction of the fetus as a self-contained, free-floating object under the watchful eye of scientific and medical surveillance is tied to its construction as a subject under the law and the myth of objectivism whereby the scientist is conceptualized as "authorized ventriloquist for the object world" (Haraway 1997, 24). Absent from this picture is the pregnant woman and accountability for the intra-actions of particular medical, biological, scientific, and legal practices (including the construction of the "object of investigation," its connection to the legal construction of the fetus as a subject, the exclusions enacted by the construction, and the epistemological,

ontological, and ethical consequences). That is, while Casper argues that the reduction of pregnant women to technomaternal environments for fetal patients is a consequence of constructing the fetus as an active agent, I am arguing that this reduction is tied to the specific constitution of objects and subjects in the intra-action of specific apparatuses of bodily production and not to fetal agency per se. In other words, I am calling into question the presumed alignment of agency and subjectivity and arguing that it is the attribution of subjectivity, not agency, that has played such a crucial role in abortion debates in the United States since the 1980s. In particular, in my agential realist account, the crucial point is that the fetus be understood in relation to its objective referent.

From the perspective of agential realism, the fetus is not a preexisting object of investigation with inherent properties. Rather, the fetus is a *phenomenon* that is constituted and reconstituted out of historically and culturally specific iterative intra-actions of material-discursive apparatuses of bodily production. The fetus as a phenomenon "includes" the apparatuses or phenomena out of which it is constituted: in particular, it includes the pregnant woman (her uterus, placenta, amniotic fluid, hormones, blood supply, nutrients, emotions, etc., as well as her "surroundings" and her intra-actions with/in them) and much more.[44] The object of investigation is constructed through the enactment of particular cuts and not others. Which cuts are enacted are not a matter of choice in the liberal humanist sense; rather, the specificity of particular cuts is a matter of specific material practices through which the very notion of the human is differentially constituted. In particular, it is not a given that the object is a self-contained, free-floating body located inside a technomaternal environment; rather, this identification is the result of particular historically and culturally specific intra-actions of material-discursive apparatuses. For example, the racialized and classed construction of an "epidemic of infertility," which "contrary to its popular presentation as a problem that overwhelmingly afflicts white, affluent, highly educated women, is actually [a problem that is] higher among the nonwhite and poorly educated," has served to justify the expanded development of a range of new reproductive technologies for the production of white babies. Simultaneously, it has deflected attention from accountability for environmental racism, which is thought to be responsible for the existing racial asymmetry in the actual statistics (Hartouni 1997, 45). The new reproductive technologies work to reproduce the fetus and particular race relations marking more women's bodies than just the particular ones that serve as "maternal environments."

Recall how agency and accountability are tied together. According to agential realism, agency cannot be designated as an attribute of subjects or objects, which are themselves constituted through specific practices. Furthermore, apparatuses are not mere physical instruments that are separable from the objects of observation. Rather, apparatuses must be understood as phenomena made up of specific intra-actions of humans and nonhumans, where the differential constitution of the "human" (and its "others") designates an emergent and ever-changing phenomenon. Agency is not about choice in the liberal humanist sense; agency is about the possibilities and accountability entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by those practices.

The fact that the fetus "kicks back," that there are fetal enactments, does not entail the concession of fetal subjectivity. Recall that the fetus is a complex material-discursive phenomenon that includes the pregnant woman in particular, in intra-action with other apparatuses. And fetal enactments include the iterative intra-activity between the pregnant woman and the object that gets called the "fetus." This formulation exposes the recently intensified discourse of hypermaternal responsibility as a displacement of the real questions of accountability onto the pregnant woman, who is actively constructed as a "mother" bearing full responsibility, and the full burden of accountability, for fetal well-being, including biological and social factors that may be beyond her control.[45] The real questions of accountability include accountability for the consequences of the construction of fetal subjectivity, which emerges out of particular material-discursive practices; accountability for the consequences of inadequate health care and nutrition apparatuses in their differential effects on particular pregnant women; accountability for the consequences of global neocolonialism, including the uneven distribution of wealth and poverty; and many other factors.

There are different possibilities for reworking the material-discursive apparatuses of bodily production, including (but not limited to) acts of subversion, resistance, opposition, and revolution. The changes that are enacted will depend on the specific nature of the agential intra-actions (not all possibilities are open at each moment), which may include the distribution of agency over human, nonhuman, and cyborgian forms, or rather the iterative (re)constitution of humans and nonhumans through ongoing agential enactments. Learning how to intra-act responsibly within and as part of the world means understanding that we are not the only active beings—though this is never justification for deflecting that responsibility onto other entities. The acknowledgment of "nonhuman agency" does not lessen human accountability; on the contrary, it means that accountability requires that much more attentiveness to existing power asymmetries.

Acts of subversion, for example, include, but are not limited to, changes in the specific material reconfigurations of apparatuses through the enfolding of particular subversive resignifications. Other possibilities include changes in the economic conditions of people's lives. Each case requires that we be attentive to the intra-twining of material and discursive constraints and conditions. In an article entitled "Gynogenesis: A Lesbian Appropriation of Reproductive Technologies," Elizabeth Sourbut (1996) explores the subversive potential of new reproductive technologies. The subversive potential of gynogenesis, in which the genetic material from one egg is added to a second egg to create an embryo from two female parents, exploits "the contradiction between the 'unnaturalness' of test-tube conception, and the supposed 'naturalness' of the [patriarchal, heteronormative] institutions these techniques are meant to perpetuate" (S. Franklin 1990, 226). To date, none of the (mouse) gynogenones have developed to term.[46] It appears that this is due to some "gene imprinting" mechanism that is not yet understood: that is, all the necessary genes are there, but they just have to be "turned on and off" at appropriate times. Gene imprinting is the name that geneticists have assigned to this form of nonhuman agency. This is not to suggest that this naming and this assignment are simply descriptive; on the contrary, they must be understood performatively. Future technoscientific intra-actions leading to the successful development of gynogenones will depend on understanding the nature of this form of nonhuman agency and how it changes in intra-action with agential shifts in the material-discursive apparatuses of bodily production; intra-acting responsibly with/in and as part of the world will require thinking critically about the boundaries, constraints, and exclusions that operate through particular material-discursive apparatuses intra-acting with other important apparatuses.

While gynogenesis has not yet been realized, the new reproductive technologies have already been enlisted for purposes other than those to which they were intended. "There are lesbian couples in the United States where one partner is implanted with an embryo created by her lover's ovum and donor sperm. That partner, technically a surrogate, then gets to give birth to her lover's baby" (Martin 1993, 358).[47]

Needless to say, while subversive acts play on the instability of hegemonic apparatuses, they—like the hegemonic attempts to contain contradictions and add stability to the apparatuses—include reinforcing and destabilizing elements. In this case, the destabilizing effects of (mis)appropriations of new reproductive technologies, including challenges to the patriarchal and heteronormative structure, are accompanied by the reinforcement of class asymmetries and the cultural overvaluation of raising children that are genetic offspring. Accountability and responsibility must be thought of in terms of what matters and what is excluded from mattering.

3-D ULTRASONOGRAPHY: MOVING BEYOND THE SURFACE

Today the piezoelectric transducer is being enfolded into a new and powerful technoscientific practice. Called most commonly by the name of "3-D ultrasonography," it is also known as "volumic echography," "volume sonography," and "ultrasound holography." The idea behind this new technology is close to half a century old, but it has started to materialize only within the past decade or so, now that the computer technology has developed sufficiently, and it is only recently that a concerted effort has begun to integrate it into medical practice in this country and abroad.[48]

If the standard-fare two-dimensional ultrasonographic technology takes great advantage of the high status accorded to the visual in our epistemological economy, then the new three-dimensional technology raises the stakes by orders of magnitude, inducing a kind of manic exhilaration over the epistemic earnings potential of this virtual reality tour of the body that makes real-time two-dimensional ultrasonography seem downright rudimentary. Unlike the two-dimensional images, which have an eerie "x-ray" quality to them, the new three-dimensional images have a "natural," all-too-familiar quality: the images are so "lifelike" that they seduce the viewer into thinking that the representation of the object is isomorphic with the object itself; the image seems to be just like what we would see with our own eyes, but even better (if only our visual faculties had a zoom feature, the ability to rotate images without physically moving around an object, and the ability to slice away with a "virtual scalpel" any opaque section of the object that is obstructing our view!).[49]

How does this new technology work? Recall that the ultrasound images that are most familiar to us are created by imaging a single two-dimensional cross section of the object. Hence, when a section of the fetus is imaged, the sonogram has that "x-ray" look to it: the body is rendered "transparent" because a cross-sectional view helps itself to its own conception of a "surface"; the surface that it defines is a single two-dimensional slice through the body. The new three-dimensional technology works by scanning successive close planes of the object and storing the information in a computer until the entire object is scanned. The computer integrates the two-dimensional images, producing a three-dimensional mapping of the entire volume of the object. The surface that becomes the focus of study is constructed through this computational integration of information. In this way, different surfaces of the body can be rendered from the information about the volume, including the familiar surfaces of the body. Hence the images viewed on the computer screen can restore that feel of opacity to which we are visually accustomed: the surface materializes derivatively from the volume information, enabling this technology to render the image of the body intelligible to us in a way that matters—constituting this material-discursive practice as a particularly poignant instrument and vector of power.

Of course, this apparatus of bodily production is materializing in intraaction with other practices, like those that contribute to the abortion debate in this country. Not surprisingly, this technology is already being enjoined in this debate and has been hailed by some antiabortionists as *the* final arbiter in providing a direct window on the truth.

There are many other uses of 3-D ultrasonography, including nonobstetrical ones: it has, for example, the potential to drastically increase our understanding of human biology and to significantly change surgical practices.

Understanding the nature of the phenomena produced by this powerful technology will require a more complex understanding of bodies than we currently have. A biological theory of the body in isolation will not do. A theory of the constitution of any single surface of the body is not sufficient. Three-dimensional ultrasonography is both a symbol and a practice pointing to the necessity of knowing how to read the relationship between surface and volume. Might this powerful technology produce important insights concerning the nature of this relationship or the consequences of using different mappings? Might the "virtual scalpel" provide some insight into the nature of boundary-drawing practices? Might feminist theory provide crucial insights into the practice of three-dimensional ultrasonography, such as locating the objective referent, understanding the epistemic and psychic seductiveness of visual representations, understanding the epistemological and ontological consequences of making particular virtual and nonvirtual cuts, and getting practitioners to reflect on the ways in which this technology has the potential to both erase and initiate the patient's subjectivity?[50] There is a need for feminists to be involved in the practices of science, technology, and medicine, the theorization of technoscientific practices, and the theorization of the social, the cultural, and the political. There is a need to understand the laws of nature as well as the law of the father.[51] But understanding and reworking different disciplinary apparatuses in isolation won't suffice. Intra-actions matter.

SIX

Spacetime Re(con)figurings: Naturalcultural Forces and Changing Topologies of Power

During a transatlantic flight from New York to London, at a cruising altitude of thirty-five thousand feet, a communications link between an Intel-based notebook computer, perched on a tray in front of the passenger in seat 3A of the Boeing 747, and a Sun workstation on the twentieth floor in a Merrill Lynch brokerage house in Sydney initiates the transfer of investment capital from a Swiss bank account to a corporate venture involving a Zhejiang textile mill. The event produces an ambiguity of scale that defies geometrical analysis. Proximity and location become ineffective measures of spatiality. Distance loses its objectivity—its edge—to pressing questions of boundary and connectivity. Geometry gives way to changing topologies as the transfer of a specific pattern of zeros and ones, represented as so many pixels on a screen, induces the flow of capital and a consequent change in the material conditions of the Zhejiang mill and surrounding community. With the click of a mouse, space, time, and matter are mutually reconfigured in this cyborg "trans-action" that transgresses and reworks the boundaries between human and machine, nature and culture, and economic and discursive practices.[1]

The view from somewhere, social location, positionality, standpoint, contextuality, intersectionality, and local knowledges—all are notions that line many a feminist toolbox, for good reasons. And yet these effective and useful tools often implicitly rely on a container model of space and a Euclidean geometric imaginary.[2] The view of space as container or context for matter in motion—spatial coordinates mapped via projections along axes that set up a metric for tracking the locations of the inhabitants of the container, and time divided into evenly spaced increments marking a progression of events—pervades much of Western epistemology. As the geographer Edward Soja points out: "This essentially physical view of space has deeply influenced all forms of spatial analysis, whether philosophical, theoretical or empirical, whether applied to the movement of heavenly bodies or to the history and landscape of human society. It has also tended to imbue all things spatial with a lingering sense of primordiality and physical composition, an aura of objectivity, inevitability, and reification" (Soja 1989, 79).

Cultural geographers have contested this view of space as a neutral backdrop against which events unfold. A paradigmatic shift occurred with Henri Lefebvre's insistence that space is not a given, but rather that space and society are mutually constituted and that space is an agent of change, that is, it plays an active role in the unfolding of events. Building on David Harvey's theory of geographical historical materialism, Donna Haraway argues that not only class but other material-social practices, such as racialization and gendered sexualization, need to be understood as constituting "bodies-in-the-making and contingent spatiotemporalities" (Haraway 1997, 294). By way of example, Haraway offers the following observation concerning the role that the container model of spatialization plays in the fetishization of gene maps in molecular biology practices:

> Spatialization as a never-ending, power-laced process engaged by a motley array of beings can be fetishized as a series of maps whose grids nontropically locate naturally bounded bodies (land, people, resources—and genes) inside "absolute" dimensions such as space and time. The maps are fetishes in so far as they enable a specific kind of mistake that turns process into nontropic, real, literal things inside containers. (1997, 136)

Haraway's critique of models of spatialization that reify complex practices and make them into things inside containers captures some of the key elements of the kinds of shifts in refiguring space, time, and matter that I am interested in exploring here, including the dynamic and contingent materialization of space, time, and bodies; the incorporation of material-social factors (including gender, race, sexuality, religion, and nationality, as well as class) but also technoscientific and natural factors in processes of materialization (where the constitution of the "natural" and the "social" is part of what is at issue and at stake); the iterative (re)materialization of the relations of production; and the agential possibilities and responsibilities for reconfiguring the material relations of the world. I offer a systematic development and further elaboration of these and related ideas. I consider how agential realism can contribute to a new materialist understanding of power and its effects on the production of bodies, identities, and subjectivities. Central to my analysis is the agential realist understanding of matter as a dynamic and shifting entanglement of relations, rather than a property of things. I develop and explore these ideas in relation to the political theorist Leela Fernandes's ethnographic study of the materialization of the relations of production, where questions of political economy and cultural identity formation are both at work on the shop floor.

Following Ruth Wilson Gilmore's suggestion that we replace the politics of location with a politics of possibilities (Gilmore 1999), in this chapter I aim to dislocate the container model of space, the spatialization of time, and the reification of matter by reconceptualizing the notions of space, time, and matter using an alternative framework that shakes loose the foundational character of notions such as location and opens up a space of agency in which the dynamic intra-play of indeterminacy and determinacy reconfigures the possibilities and impossibilities of the world's becoming such that indeterminacies, contingencies, and ambiguities coexist with causality.[3] These reconceptualizations make possible normative analyses crucial to critical political practices without the need for the usual anchor to some conception of fixity.[4] Crucially, these considerations bring into relief the important task of rethinking current conceptions of dynamics (including power dynamics).

Agential realism is an epistemological and ontological framework that cuts across many of the well-worn oppositions that circulate in traditional realism versus constructivism, agency versus structure, idealism versus materialism, and poststructuralism versus Marxism debates.[5] In its reformulation of agency and its analysis of the productive, constraining, and exclusionary nature of naturalcultural practices, including their crucial role in the materialization of *all* bodies, agential realism goes beyond performativity theories that focus exclusively on the human/social realm. Agential realism takes into account the fact that the forces at work in the materialization of bodies are not only social and the bodies produced are not all human. It also provides a way to incorporate material constraints and conditions and the material dimensions of agency into poststructuralist analyses. In these and other important ways, agential realism diverges from feminist postmodern and poststructuralist theories that acknowledge materiality solely as an effect or consequence of discursive practices. These latter approaches lack an account of materiality as an agentive and productive factor in its own right, thereby reinstituting the equation between matter and passivity that some of these approaches proposed to unsettle. Additionally, they leave un(der)theorized a host of pressing questions: What is meant by the claim that discourses have material consequences? What is the relationship between discourse and materiality such that discourse can work its effects? Is there any sense in which materiality might be said to constrain discourses? If so, how? Do material reconfigurations have discursive consequences? What is it about our current material and discursive conditions that questions concerning the material consequences of discourses and the discursive consequences of materiality seem to preclude each other? This is not to say that such theories do not provide crucial philosophical and political insights. However, critics have noted that they prove inadequate in the face of one of the litmus tests of viable critical social theories: "to *explain* the relation between economic forces—like the formation of new markets through colonization, shifting centers of production, or the development of new technologies—and the reformation of subjectivities" (Hennessy 1993, 25; italics in original). And this is just a short list of material forces that matter.

At the same time, agential realism's reconceptualization of materiality diverges from traditional Marxist conceptions of materiality as strictly economic, and from some post-Marxist conceptualizations that understand it as purely social. Agential realism advances a new materialist understanding of naturalcultural practices that cuts across these well-worn divides.

Leela Fernandes's work also makes significant inroads in this regard, advancing our understanding of social reality in her theorization of the relationship between structural and discursive forces. For Fernandes, as well as for other feminist theorists, like Rosemary Hennessy and Ruth Wilson Gilmore, structural relations are not about structures in the structuralist's sense, and poststructuralism is emphatically not an antidote to Marxism but rather is usefully appropriated as a corrective elaboration of orthodox forms of structural analysis.[6] As these theorists emphasize, understanding class as a dynamic variable with integral cultural, ideological, and discursive dimensions does not diminish, but indeed is necessary to, a thoroughgoing analysis of economic capital in its materiality. Likewise, it is important to recognize the material dimensions of cultural economies.

In this chapter, I diffractively read Fernandes's notion of the structural-discursive relations of power and an agential realist understanding of material-discursive relations of power through each other.[7] This makes it possible to provide a deeper understanding of the nature of structural relations in their materiality and their relationship to discourses, and a new understanding of the dynamics of power relations. It will also suggest a need for remilling some of our most important feminist tools.[8]

PRODUCING WORKERS/PRODUCING STRUCTURES: THE SHOP FLOOR AS A MATERIAL-DISCURSIVE APPARATUS OF BODILY PRODUCTION

Issues of political economy and cultural identity are inseparable. Leela Fernandes's analysis of the structural and ideological workings of power in a Calcutta jute mill gives strong empirical support for this claim. In *Producing Workers*, Fernandes (1997) employs analytical tools from poststructuralist and Marxist schools of thought, meshing and shifting the gears of these heavy machineries to obtain an understanding of the multiple technologies through which the working class is produced. Disassembling the tenacious assumption in research on labor that "class structure is a uniform, objective 'purity' while other forms of social identity such as gender, religion, and ethnicity are symbolic or ideological forces that either divide or intersect with class identity" (59), Fernandes exposes the manifold connections and detailed intra-(re)workings of identity categories through an examination of shop floor dynamics as they materialize in the course of the everyday lives of the workers.

What motivates Fernandes's study is the following question: Why did the economic crisis in the Indian jute industry in the 1980s result in the differential displacement of women from the jute labor force? Fernandes's topic isn't sexy. It isn't at the forefront of the new technologies. Sewing machines, weaving machines, and other textile machinery line the factory floors; there isn't a DNA-sequencing capillary electrophoresis spectrometer, photolithograph system, or any other device of the new bio-, info-, and nano- technologies anywhere in sight. Fernandes's attention is on what happens on the factory floor, including union politics and the role of religious practices in workers' lives. She hasn't chosen a research site that typifies new capitalist forms of production, distribution, and consumption with their emphasis on service economies, immaterial labor, outsourcing, subcontracting, supply chain economics, flexible accumulation, empire building, deterritorialization, the rhizomic resistance of the multitudes, and the politics of globalization; which is not to say that this is an exceptional site that is walled off from the workings of the latest stage of capitalist production, on the contrary. Fernandes is not interested in building a case for exceptionalism. Indeed, her study does not take exceptionalism (including U.S. exceptionalism) or the dichotomy between the modern and the traditional for granted. Fernandes's study is not a return to the same old venues or the same old methods. Much more is at stake on the shop floor than the production of salable products. The material conditions of the shop floor performatively produce relations of class and other forms of cultural identity in the intra-action of humans and machines. Fernandes's focus is on the detailed dynamics of shop floor relations with an eye toward understanding how production works and doesn't work and for whom. How is difference iteratively produced? What local forms does it take? What differences do differences in production make for the production of different differences?

Fernandes attends to the (re)production of structural relations of difference by paying close attention to ongoing contests over space, time, and movement in the life of the factory. For example, Fernandes examines the gendered and classed spatialization of the shop floor to look for clues about the ways in which gender and class relations are (re)produced:

> The "structural" dimension of class can be thought of as the ways in which workers are positioned on the factory floor, through recruitment practices and a particular division of labor. This positioning of workers is contingent on the politics of gender and community, since such identities are instrumental in decisions regarding the positioning of workers; thus, gender and community are integral to the class "structure." Meanwhile, the gendering of space signifies particular kinds of class hierarchies between workers and managers and between male and female workers. (Fernandes 1997, 59)[9]

Fernandes uses this examination of the gendering of space to argue that "gender and community are integral to class 'structure' " (59). That is, class itself needs to be understood as "a product of dynamic and contested political processes at the local level of shop-floor politics" (58).

It is important not to mistake this claim for a demotion of class to the realm of the merely ideological/cultural/discursive. A potential misunderstanding of this nature rests on at least three false assumptions that Fernandes calls into question: (1) that economic categories alone are material, and social categories are not; (2) that class is an exceptional identity category; and (3) that identity categories such as class, gender, nationality, caste, and religion are separately determinate attributes of individuals, and an understanding of social dynamics is a matter of knowing how these social factors interact with each other.[10] For Fernandes, class is about economic capital, and at the same time, the "economic" is not merely about class (i.e., the working class is discursively and structurally produced through class, gender, and community). Her shift from a traditional conception of class that assumes that capitalist production is experienced in the same way by all workers all over the world to an understanding of class structures as dynamic and local products goes hand in hand with her insistence that "gender represents a structural force and is not limited to a discursive or symbolic category" (11–12). The gears of the capitalist machinery—which must be understood as different local and contested forms of the global political economy—are simultaneously materially and discursively produced. Fernandes rejects assembly-line notions of identities as analytically identical and interchangeable parts, and she eschews the notion that identities work in lock step as parallel gears in a single assemblage. The dynamics, as

Fernandes describes them, are perhaps more akin to a differential gear assemblage in which the gear operations literally work through one another and yet the uneven distribution of forces results in, and is the enabling condition for, different potentials and performances among the gears.

Fernandes appropriates and extends Foucault's analysis of the important productive effects of disciplinary regimes of power that "partitions as closely as possible time, space, and movement" (Foucault 1977, 137). She argues that "structures" should be understood "as the codification of power through movement, space, and position" (Fernandes 1997, 175), and that "the system of codification that controls time, disciplines movement and partitions space codes workers' bodies through meanings of gender, caste, and ethnicity. If, as Foucault asserts, 'discipline organizes an analytical space' (1979, 143), such techniques of power are in effect employed in the task of producing particular analytical and material borders between class, gender, and community" (Fernandes 1997, 59). I read Fernandes as saying that while disciplinary regimes of power operate through the production of individual subjects, this mode of operation destabilizes, reconfigures, and stabilizes new structural relations of power in reconfiguring the material borders between classes, genders, and communities that mark these very bodies in their materializing subjectivities. In contrast to those who would interpret Foucault's microphysics of power as a refutation of the importance—indeed, the very existence—of structural relations, Fernandes takes Foucault's formulation as an opportunity to rethink the nature and dynamics of structural relations. According to Fernandes, "structure does not represent a set of transcendental, objective determinants but is shaped by modes of representation and meanings that social actors . . . give to their positions and activities" (Fernandes 1997, 137). In other words, structures are not an external set of relations but "force relations immanent in the sphere in which they operate" (Foucault 1978). Furthermore, structures are not only productive; they are themselves produced through the very practices of subject formation that Foucault discusses.

How is Fernandes's claim to be understood? In what sense are structural relations produced and what does this production entail? What is the nature of the processes that "shape" these relations? What is the relationship between the material and discursive dimensions of power relations? How are we to understand the nature of power dynamics? Of materiality? These are some of the questions that I want to explore in diffractively reading Fernandes's powerful insights concerning the structural-discursive relations of power and agential realism through each other.

I begin by reviewing some key points about agential realism that are particularly relevant to this discussion and then proceed to discuss the example at hand. I propose that the shop floor dynamics be understood in terms of the intra-action of "material-discursive apparatuses of bodily production" —that is, the dynamic intra-workings of the instruments of power through which particular meanings, bodies, and boundaries are produced.[11] Importantly, apparatuses are not external forces that operate on bodies from the outside; rather, apparatuses are material-discursive practices that are inextricable from the bodies that are produced and through which power works its productive effects. Apparatuses are phenomena, material configurations/reconfigurings, that are produced and reworked through a dynamics of iterative intra-activity. This dynamics entails a rethinking of the nature of causality and the role of exclusions in creating the conditions of possibility for contesting and iteratively remaking apparatuses. That is, agential realism does not simply pose a different dynamics (substituting one set of laws for another); it introduces an altogether different understanding of dynamics. What is at issue is not merely that the form of the causal relations are changed, but the very notions of causality, agency, space, time, and matter are all reworked. For example, agency—rather than being thought in opposition to structures as forms of subjective intentionality and the potential for individual action—is about the possibilities for changing the configurations of spacetimematter relations. I discuss the implications of these important shifts in what follows. Using this account of naturalcultural practices makes it possible to attend to the changing "multiplicity of force relations immanent in the sphere in which they operate" (Foucault 1978, 93) where the forces are not merely social, and the bodies produced are not merely human. That is, power is rethought in terms of its overall materializing potential.

TOWARD A POLITICAL ECONOMY OF APPARATUSES, OR HOW APPARATUSES WORK

How do machines work? What kinds of work do machines do? What role do humans play in the operation and production of machines? What role do machines play in the production of other machines and humans and in the reconfiguring of human-machine boundaries and relations? What happens when machines stop working? Could this form of work stoppage be considered a form of machinic agency?

In an article entitled "Mediating Machines," the historian of science Norton Wise contends that machines mediate societal values in the production of knowledge. He argues, for example, that the steam engine "simultaneously instantiates 'labor value' in political economy and 'work' in engineering mechanics, thereby identifying the two concepts in the region of their common reference." This "partial identification," he claims, "carries with it a structural analogy between a network of concepts from political economy and a similar network in natural philosophy, providing a potent heuristic for the reformulation and further development of dynamics" (Wise 1988, 77). By way of example, Wise begins by pointing to the fact that in 1845, before the development of his work-centered perspective on dynamics (1845–62), William Thomson (Lord Kelvin) began to "regard the idea of natural agency—electric, magnetic, thermal, etc.—as an expression of the capacity to produce work, and thus to regard natural systems as engines" (Wise 1988, 80).

The productive role of apparatuses in linking issues of natural philosophy, political economy, and human and nonhuman forms of agency is one of the central themes of this chapter. However, the analysis that I offer rejects the notion that machines or apparatuses play a "mediating" role. A machine model engineered to explain the influence of social factors on the natural sciences will inevitably be a lopsided device built on a foundational difference between nature and culture. The idea that there are two separate entities or realms of practice influencing one another in determinate regions of overlap is premised on Newtonian conceptions of causality, dynamics, space, and time, and the Newtonian belief in the prior existence of separately determinate bounded and propertied entities and practices. What's missing from this analytical engine is not merely a symmetrical accounting of influence between the natural sciences and political economy, but a model of analysis that isn't a Newtonian instrument.

The shift from Newton's clockwork to Thompson's engine is but a minor mutation when compared to the discontinuous changes that have occurred during the twentieth century in the nature of machines and machinic agency, and our understanding of them.[12] Taking these changes seriously entails a reassessment of the working of all machines, even clockworks, steam engines, and devices that a Newtonian would recognize. It also suggests that the shifts in the epistemological economy of natural philosophy and in the natural philosophy of political economy that have contributed (and continue to contribute) to the production of these changes have more to do with the material entanglement of political and scientific practices than a mediated negotiation between dissimilar systems. I will not offer a historical analysis of these entanglements here. Rather my goal is to put agential realism (an account of naturalcutural practices which takes seriously insights from some of our best scientific and social and political theories) to work in thinking about the ways in which particular entanglements matter to the production of subjects and objects.

In chapter 3, I presented a detailed exposition of Bohr's analysis of the epistemological work that an apparatus does. Bohr argues that classical physics seriously underestimates and undercounts the contribution that apparatuses make. Apparatuses are not mere instruments serving as a system of lenses that magnify and focus our attention on the object world, rather they are laborers that help constitute and are an integral part of the phenomena being investigated. Furthermore, apparatuses do not simply detect differences that are already in place; rather they contribute to the production and reconfiguring of difference. The failure to take proper account of the role of apparatuses in the production of phenomena seriously compromises the objectivity of the investigation. Accounting for apparatuses means attending to specific practices of differentiating and the marks on bodies they produce.

As I explained in chapter 4, Bohr's account of the apparatus is limited in important respects. Bohr does not attend to important social dimensions of scientific practices, and he fails to offer a consistent account of the role of the subject in these practices and the role of the apparatus in the production of the subject. In that chapter I call upon the insights of social and political theorists to help illuminate particular aspects of the apparatus that Bohr's account leaves unanalyzed. I also discuss some of the limitations of these approaches and consider the possibility of using Bohr's insights to inspire productive emendations and elaborations of these accounts. For example, I argue that while Foucault and Butler attend to the materialization of human bodies as constituted through social forces, they take for granted the materiality of nonhuman beings/bodies and do not consider the productive workings of natural forces. This imbalanced accounting practice translates into an asymmetry in the accounting of material and discursive, natural and cultural, and spatial and temporal, factors in their respective works.[13] These theorists also leave unexamined important ways in which matter is an agentive factor in processes of materialization. My approach is to diffractively read these important insights from natural and social theories through one another in an effort to produce an account of naturalcultural practices and agencies that attends to the production of objects and subjects, the materialization of human and nonhuman bodies, and the entanglement of material relations (including those that get named social, political, economic, natural, cultural, technological, and scientific, rather than presuming separate factors and domains of operation from the outset).[14] One of the goals, as discussed, is to build an apparatus that is attentive to the nature of specific entanglements. I'm not going to review that analysis here but I do want to highlight some of the significant changes that are entailed in this rethinking of ontology, epistemology, and ethics.

Dynamics are about change. Feminists and other theorists commonly invoke the notion of a power dynamics. In doing so, they often worry about what is meant by power and how it operates, but they assume that the notion of dynamics is a settled and unproblematic concept. Agential realism entails a rethinking of both notions: power and dynamics.

How much of our understanding of the nature of change has been and continues to be caught up in the notion of continuity? For Newton, physicist extraordinaire, inventor of the calculus, author of biblical prophesies, uniter of heaven and earth, continuity was everything, or very nearly. It gave him the calculus. And the calculus gave voice to his vision of a deterministic world: placing knowledge of the future and past at Man's feet. Prediction and retrodiction are Man's for the asking, the price is but a slim investment in what is happening in an instant, any instant. Each bit of matter, whether the size of a planet or an atom, traces out its designated trajectory specified at the beginning of time. Effects follow their causes end on end and each particle takes its preordained place with each tick of the clock. The world unfolds without a hitch. Strict determinism operates like a well-oiled machine. Nature is a clockwork, a windup toy the Omniscient One started up at time $t = 0$ and then even He lost interest in and abandoned (or perhaps remembers now and again and drops in to do a little tuning up). The universe is a tidy affair indeed. The presumed radical disjuncture between continuity and discontinuity was the gateway to Man's stewardship, giving him full knowability and control over nature. Calculus is the escape hatch through which Man takes flight from his own finitude. Man's reward: a God's eye view of the universe, the universal viewpoint, the escape from perspective, with all the rights and privileges accorded therein. Vision that goes right to the heart of matter, unmediated sight, knowledge without end, without responsibility. Individuals with inherent properties there for the knowing, there for the taking. Matter is discrete but time is continuous. Nature and culture are split by this continuity and objectivity is secured as externality. We know this story well, it's written into our bones, in many ways we inhabit it and it inhabits us.

The quantum disrupts this tidy affair. A bit of a hitch, a tiny disjuncture in the underlying continuum, and causality becomes another matter entirely.

Strict determinism is stopped in its tracks, but the quantum does not leave us with free will either, rather, it reworks the entire set of possibilities made available. Agency and causality are not on-off affairs. This tiny disjuncture, existing in neither space nor time, torques the very nature of the relation between continuity and discontinuity to such a degree that the nature of change changes from a rolling unraveling stasis into a dynamism that operates at an entirely different level of "existence," where "existence" is not simply a manifold of being that evolves in space and time, but an iterative becoming of spacetimemattering (as I explain in chapter 4). Space, time, and matter are intra-actively produced in the ongoing differential articulation of the world. Time is not a succession of evenly spaced intervals available as a referent for all bodies and space is not a collection of preexisting points set out as a container for matter to inhabit. Intra-actions are nonarbitrary nondeterministic causal enactments through which matter-in-the-process-of-becoming is iteratively enfolded into its ongoing differential materialization; such a dynamics is not marked by an exterior parameter called time, nor does it take place in a container called space, but rather iterative intra-actions are the dynamics through which temporality and spatiality are produced and iteratively reconfigured in the materialization of phenomena and the (re)making of material-discursive boundaries and their constitutive exclusions.

The existence of the quantum discontinuity means that the past is never left behind, never finished once and for all, and the future is not what will come to be in an unfolding of the present moment; rather the past and the future are enfolded participants in matter's iterative becoming. Becoming is not an unfolding in time, but the inexhaustible dynamism of the enfolding of mattering.

According to agential realism, causality is neither a matter of strict determinism nor one of free will. Intra-actions always entail particular exclusions, and exclusions foreclose the possibility of determinism, providing the condition of an open future. But neither are anything and everything possible at any given moment. Indeed, intra-actions iteratively reconfigure what is possible and what is impossible—possibilities do not sit still. One way to mark this might be to say that intra-actions are constraining but not determining. But this way of putting it doesn't do justice to the nature of "constraints" or the dynamics of possibility. Possibilities aren't narrowed in their realization; new possibilities open up as others that might have been possible are now excluded: possibilities are reconfigured and reconfiguring.[15] There is a vitality to intra-activity, a liveliness, not in the sense of a new form of vitalism, but rather in terms of a new sense of aliveness.[16] The world's effervescence, its exuberant creativeness can never be contained or suspended. Agency never ends; it can never "run out." The notion of intra-actions reformulates the traditional notions of causality and agency in an ongoing reconfiguring of both the real and the possible.

In particular, agency is cut loose from its traditional humanist orbit. Agency is not aligned with human intentionality or subjectivity. Nor does it merely entail resignification or other specific kinds of moves within a social geometry of antihumanism. The space of agency is not only substantially larger than that allowed for in most poststructuralist accounts, but also, perhaps rather surprisingly, larger than what liberal humanism proposes. Significantly, matter is an agentive factor in its iterative materialization. Furthermore, the future is radically open at every turn and this open sense of futurity does not depend on the clash or collision of cultural demands. Rather, it is inherent in the nature of intra-activity—even when apparatuses are primarily reinforcing, agency is not foreclosed. Furthermore, the space of agency is not restricted to the possibilities for human action. But neither is it simply the case that agency should be granted to nonhumans as well as humans, or that agency can simply be distributed willy-nilly over nonhuman and human forms.

Crucially, agency is a matter of intra-acting; it is an enactment, not something that someone or something has. Agency is doing/being in its intra-activity. It is the enactment of iterative changes to particular practices—iterative reconfigurings of topological manifolds of spacetimematter relations—through the dynamics of intra-activity. Agency is about changing possibilities of change entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by those practices in the enactment of a causal structure. Particular possibilities for (intra-)acting exist at every moment, and these changing possibilities entail an ethical obligation to intra-act responsibly in the world's becoming, to contest and rework what matters and what is excluded from mattering.

As Foucault and Butler emphasize, power is not an external force that acts on a subject; there is only a reiterated acting that is power in its stabilizing and sedimenting effects—only now, in my agential realist account, "the moving substrate of force relations" (Foucault 1978, 92) is not limited to the social.[17] That is, *the forces at work in the materialization of bodies are not only social, and the materialized bodies are not all human*. Furthermore, the productive nature of regulatory and other naturalcultural practices is to be understood in terms of the causal nature of intra-activity. Crucial to an agential realist conception of power is a reworking of causality as intra-activity. Indeed, what is at issue is the very nature of causal relations: causal relations do not preexist but rather are intra-actively produced. What is a "cause" and what is an "effect" are intra-actively demarcated through the specific production of marks on bodies.

The fundamental discontinuity of quantum physics disrupts the nature of difference: the relationship between continuity and discontinuity is not one of radical exteriority but rather of agential separability, each being threaded through with the other. "Otherness" is an entangled relation of difference. Questions of space, time, and matter are intimately connected, indeed entangled, with questions of justice.

SHIFTING GEARS/SHIFTING DYNAMICS: MANIFOLD POSSIBILITIES FOR THE TOPOLOGICAL RE(CON)FIGURING OF RELATIONS OF POWER

> Class is not this or that part of the machine, but *the way the machine works* . . . the friction of interests—the movement itself, the heat, the thundering noise. . . . class itself is not a thing, it is a happening.
>
> —E. P. THOMPSON, *The Poverty of Theory and Other Essays*

Leela Fernandes's book, *Producing Workers*, is a detailed study of the structural relations of power as they are iteratively (re)produced and contested on the shop floor of a Calcutta jute mill. Fernandes uses the spatial positioning of workers on the shop floor as a material marker of the structural dimensions of class.[18] She cleverly focuses on the material constraints that restrict the positioning and constrain the movement of workers throughout the factory rather than attempting to capture a single deterministic trajectory of power. Indeed, such an idealized trajectory would be meaningless, since it misses the important role that multiple intra-actions, exclusions, and agencies play in the dynamics of power.

In reading Fernandes's work, it is important to notice that material constraints cannot be understood as immutable obstacles in an otherwise unlimited space of freedom. Furthermore, they are not to be interpreted as being completely independent of discursive practices, nor reducible to them, nor as the mere endpoints of such practices. Rather, I read Fernandes's analysis of the dynamics of structural relations in terms of the contingent materialization of the shop floor: not only do the politics of space in the jute mill produce workers as appropriately disciplined subjects in intra-action with the ever-changing relations of power, but the spatiality of capitalism is itself produced through the politics of gender, community, and class and daily contests over the relations of power by those very subjects. For example, Fernandes argues that "when unions and male workers engage in this reproduction of asymmetrical gender relations, they in fact produce a scattered array of local practices and discourses that maintain the national hegemonic construction of class. In this process, they do not merely use preexisting gendered ideologies but also actively manufacture gender through the creation of particular notions of masculinity and femininity" that wind up reinforcing the powers of management and undermining attempts by the unions to successfully intervene in certain class-based—always already gendered—practices of management (Fernandes 1997, 74). In other words, Fernandes maintains that the spatiality of capitalism is produced not merely through actions of managers who carve up the production process but through the workers' own exclusionary practices as well. That is, while the mill is perhaps most obviously an ongoing process of the materialization of capital, the iterative materialization of the mill is also the outcome of the exclusionary practices of the workers themselves, but not via some linear additive dynamics. Rather, the exclusionary practices of the workers need to be understood to be part of the technologies of capitalism. The intra-action of these material-discursive apparatuses, which includes the practices of the workers as well as the managers, produces a space or structure specifically marked by the topological enfolding of gender, community, and class. In other words, the spatiality of the mill is produced through the dynamics of intra-activity and the reconfiguring and enfolding of structural relations. Structures are apparatuses that contribute to the production of phenomena, but they must also be understood as thoroughly implicated in the dynamics of power: structures are themselves material-discursive phenomena that are produced through the intra-action of specific apparatuses of bodily production marked by exclusions.[19] Structures are specific material configurations/(re)configurings of the world.

Hence, using the framework of agential realism, the jute mill can be understood as an intra-acting multiplicity of material-discursive apparatuses of bodily production that are themselves phenomena materializing through iterative intra-actions among workers, management, machines, and other materials and beings which are enfolded into these apparatuses. Importantly, materiality is rethought as a contingent and contested, constrained but not fully determined, process of iterative intra-activity through which material-discursive practices come to matter, rather than as mere brute positivity or some purified notion of the economic. It is not the case that economic practices are material, while the presumably separate set of social matters (such as gender and community identity) are merely ideological. The very nature of production is refigured as iterative intra-activity. In the case of the example considered here, this means that production is a process *not merely* of making commodities but also of making subjects, and remaking structures.[20]

Production should not be thought of as the repetition of some fixed set of processes (despite the pervasiveness of the Fordist assembly-line image it often connotes). Rather, the nature of production processes is continually reworked as a result of human, nonhuman, and cyborgian forms of agency. Indeed, as Fernandes points out, when a machine refuses to work, it may initiate a series of events: lost wages for a weaver, a fight between the weaver and the mechanic who was late fixing the machine, the intervention of management to resolve the conflict, union charges against management for mishandling the conflict, a union strike that leads to the restructuring of relations between management and workers, a reconfiguration of machines and workers on the shop floor, or a day off.

Fernandes also observes that the crowding of machines on the shop floor produces the material conditions for workers to crowd together in a way that counters management attempts to institute disciplinary practices that produce individual workers and individualize the nature of work in order to hold individual workers accountable to specified levels of production as established by the management. However, despite management's deployment of a host of low-tech surveillance techniques (e.g., chalkboards and meters installed in the weaving department) that are put in place to track individual worker productivity and hold individuals accountable, the concentration of weaving machines on the shop floor undermines these attempts to individualize the nature of work and provides numerous opportunities for workers to talk with each other. In this way humans and machines together contest the individualization of the nature of production:

> The shop floor tends to be crowded, for machines have been added at various stages in order to increase productivity. . . . The spatial concentration of workers and machines allows workers to talk to each other on the shop floor and has led to numerous complaints by managers that workers tend to gossip and loiter. Such . . . everyday acts of resistance . . . point to the contested nature of the production process and demonstrate that the control of time and movement through the production process represents a political and conflicted terrain. (Fernandes 1997, 63)

Machinic agency is part of the ongoing contestation and reconfiguring of relations of production. The point is not that management and workers become cyborgs in their relationship to machines, but rather the point is that machines and humans differentially emerge and are iteratively reworked through specific entanglements of agencies that trouble the notion that there are determinate distinctions between humans and nonhumans. Workers, machines, managers are entangled phenomena, relational beings, that share more than the air around them; they help constitute one another (e.g., in some cases machines and workers help domestic each other, in other cases they help each other run wild).[21] The entangled, contingent, and changing material conditions of the shop floor produce much more than saleable commodities and the flow of capital is but one stream in a turbulent river of agencies. This shift in theoretical perspective makes visible particular kinds of agency and possibilities for reworking unhealthy and unjust labor conditions that might otherwise be missed if it is assumed that the sole progenitors of agency are human (and only particular humans at that).

Perhaps an elaboration and extension of the differential gear assemblage metaphor that I invoked earlier will provide a useful way of envisioning this understanding of the complex nature of production. The extension that I have in mind is designed to focus attention on the fact that apparatuses are themselves phenomena. Imagine a differential gear assemblage (i.e., a gear assemblage in which the gear operations literally work through one another and in which an uneven distribution of forces results in, and is the enabling condition for, different potentials and performances among the gears) that in an ongoing fashion is being (re)configured/(re)assembled while it is itself in the process of producing other differential gear assemblages. Gears are remilled through intra-actions with other gears, and some gears are in the process of being enfolded into the assemblage as part of its ongoing process of reconfiguration. The assemblages are marked by these processes of (re)assembly. The sedimenting marks of time do not correspond to the history of any individual gear but rather are integrally tied to the genealogy of the assemblage and its changing topology, that is, to the processes of inclusion and exclusion in the reworking of the boundaries of the assemblages.[22] Imagine further that the differential gear assemblages include humans and nonhumans, where the differential constitution of "human" and "nonhuman" changes with each intra-action.[23]

I have engaged this all-too-mechanistic analogy, playing off the most pedestrian metaphor of production, in an attempt to highlight some of the shortcomings of common (mis)conceptions of production processes. For example, all too often the focus is either exclusively on the human dimensions of production, distribution, and consumption practices, narrowly conceived as that which occurs in the formal sector of the economy, or on the material culture of these practices in ways that assume separability and stable divisions between the human and the nonhuman.[24] Furthermore, notice that this proposed mutating variant of the machine metaphor for production entails a different understanding of the nature of dynamics—a dynamics in which there is an ongoing reworking of the nature of the production of the very technologies of production themselves. The dynamics of intra-activity are explicitly nonlinear, causal, and nondeterministic. Enfolding is not an arbitrary, random, or automatic process; it is a matter of iterative agential changes in the nature of production. Enfolding changes the topology of spacetime as the connectivity of the spacetime manifold and the boundaries between interior and exterior are reworked. The reconstitution of boundaries and exclusions is an agential process. The apparatuses of production are themselves produced and iteratively reworked, as is the nature of production itself. Agential realism disassembles the notion that structures are Althusserian apparatuses—rigidified social formations of power that foreclose agency and deterministically produce subjects of ideological formations. On the contrary, structures are to be understood as material-discursive phenomena that are iteratively (re)produced and (re)configured through ongoing material-discursive intra-actions.[25]

This machine is not a device assembled out of discrete gears. It would not fit neatly into a Euclidean geometrical framework. It is a topological animal that mutates through an open-ended dynamics of intra-activity. Questions of connectivity, boundary formation, and exclusion (topological concerns) must supplement and inform concerns about positionality and location (too often figured in purely geometrical terms).[26]

As an example, consider the notion of "intersectionality" introduced by feminists of color. Feminists of color who fought hard to displace hegemonic discourses that insisted on the reductive equation "women = gender" tirelessly warned against Euclidean geometrical interpretations of social location and identity formation.[27] Intersectionality, as a well-milled theoretical tool, cuts against the grain of such conceptions. In Fernandes's hands, for example, identity formation is understood not in terms of a Euclidean geometrical model but as a dynamics of changing topologies of space, time, and matter. Identity, in her account, is not about location or positionality with respect to a Euclidean grid of identification. Rather, identity formation is a contingent and contested ongoing material process; "identities" are mutually constituted and (re)configured through one another in dynamic intra-relationship with the iterative (re)configuring of relations of power. What is so striking about Fernandes's contribution is that her methodological approach enables her to follow the dynamics through which identities and power relations are mutually constituted and iteratively reworked. In particular, she keeps her eye on the way in which the structural relations of production are produced and on the dynamics of the topological reconfiguring of power relations.

Fernandes provides multiple illustrations of the topological nature of these changing dynamics. For example, Fernandes opens her book with an example of the way in which identity categories are produced through one another in following an intra-worker dispute that is transformed into a confrontation between unions and managers and results in a wildcat strike:

> The conflict had begun as a quarrel between two workers on the shop floor. A weaver was waiting for his machine to be fixed by a mechanic. The mechanic did not arrive on time, and the weaver was angry at being unable to work; since his was a piece-rated occupation, the delay had resulted in a loss of wages for the weaver. When the *mistri* (mechanic) finally arrived, an argument started; the mechanic injured the weaver with his hammer, and in the ensuing fight the mechanic was also injured. At this point the general manager and personnel manager . . . took the two to the dispensary. The general manager tried to resolve the conflict, and he made the two workers shake hands. (Fernandes 1997, 1–2)

Fernandes explains that a difference in the caste identities of the weaver and the mechanic played an important role in the union's response to the conflict and the way in which it intra-acted with the factory management:

> The incident reveals the manner in which worker resistance, such as a strike, may arise out of conflicts and social hierarchies between groups of workers. In this case the caste allegiance of the weaver shaped the union's participation and occurred at the expense of the mechanic. However, once the conflict involved a union-management confrontation, it acquired a different meaning for the participants and the workers in general. The wildcat strike rested on a link between the workers' caste positions and union mobilization. However, the meaning of the strike was not limited to this caste relationship. To many workers not involved in the conflict, the strike represented a challenge to an unfair system of authority, that is, within the capitalist system in the factory. In short, there was continual slippage between the politics of caste and class through this sequence of events. (Fernandes 1997, 3–4)

Fernandes notes that in this situation the "unions produced a form of working-class politics that was constructed through caste politics. The boundaries of class interests thus became contingent on caste hierarchies through a specifically political process that involved the participation of workers, unions, and managers in the factory" (Fernandes 1997, 4). But caste hierarchies are themselves produced: "Community identity is created through a conflicted dynamic of hegemony and resistance, a process in which community simultaneously produces and is manufactured through narratives of class and gender within a contested symbolic terrain" (89). Caste, gender, and class materialize through, and are enfolded into, one another. The nature of this enfolding matters to the changing topology, as do iterative changes to the spatiality and temporality of the shop floor, which are constitutive factors in the production of the differential patterns of mattering that constitute the shop floor in its materiality. Structural relations are contingent materialities that are iteratively reworked.[28]

One fascinating thing about Fernandes's analysis is that just when critical social accounts of the workings of power are turning to the postmodern, the posthuman, and the newly emergent, Fernandes returns to the factory floor. She does so not to show the continuing relevance of orthodox Marxist analysis, or simply because this kind of analysis is relevant to what seems to be "old" and not just to what seems to be "new," but because part of what is at stake is the reworking of temporality beyond the usual divisions between the premodern, modern, and postmodern, that is, beyond any developmental sense of temporality.[29] On the other hand, Fernandes's study is also limited in important ways. For starters, Fernandes's genealogies are less attentive to important naturalcultural forces beyond the "bounds" of the factory than what is needed in rethinking questions of scale and the topological reconfigurings that rework the terms of the local and the global.[30] Pushing Fernandes's analysis to the next level would surely entail attending to the workings and production of the causal relations themselves, especially as they are iteratively reconfigured and entangled with other modes of production. I have tried to indicate some of the further complexities of the dynamics that are at issue by considering some theoretical tools that may be useful for this further elaboration, but I have not delved into the specific details of this example and much more work is needed to grasp some of the other relevant entanglements and how they matter and for whom.

What is needed are genealogical analyses not only of the multiple apparatuses of bodily production that come to matter but also of the changing nature of the dynamics itself. Significantly, the agential nature of the iterative

reconfigurings of spacetimematter relations makes clear the need for an ethics of responsibility and accountability not only for what we know, how we know, and what we do but, in part, for what exists.

TOPOLOGICAL MANIFOLDS: SPATIALITY, TEMPORALITY, AND FUTURITY

> How we represent space and time in theory matters, because it affects how we and others interpret and then act with respect to the world.
>
> —DAVID HARVEY, *The Condition of Postmodernity*

The shop floor is not a neutral observing device or a Euclidean frame of reference that allows managers and social scientists to specify the social location of individual workers or to track the trajectories of identity formation. Rather, the apparatuses that make "position" intelligible are implicated in the iterative (re)production of particular material-discursive boundaries among workers. Not only is the notion of position itself a produced, contingent, and contested category that changes through time (not simply whose value changes with time), but "worker" is not a fixed and unitary property of individual human beings, but an actively contested and disunified—but nonetheless objective—category that refers to particular material-discursive phenomena (not individuals). Consequently, it would be inappropriate to view workers as pawns occupying different, but uniform, spaces on the chessboard of an overarching static structure called capitalism; rather, the spatiality of capitalism is itself a contested and ever-changing topology that is iteratively (re)produced through the dynamics of intra-activity and enfolding. The nature of the category "class," its intelligibility and its materiality, depends on these changing dynamics, including intra-actions with particular material-discursive practices that locally define gender and "community." "Thus, 'the working class' does not represent a singular unit but is constituted by status differences" (Fernandes 1997, 10). Likewise, gender, which "represents a type of 'structuring' category, a form of 'habitus' that produces and negotiates patterns within social and cultural life" (11), is itself a contested category whose intelligibility depends in part on the specifics of materializing structural relations (including, for example, ones that might commonly be labeled "economic"). In particular, gender is constituted through class and community and other structural relations of power. Gender, class, and community are enfolded into, and produced through, one another. The claim that class is discursively produced is not a denial of its materiality;

likewise, gender and community are no less material (and no more discursive) than class.

Material conditions matter, not because they "support" or "sustain" or "mediate" particular discourses that are the actual generative factors in the formation of subjects, but because both discourses *and* matter come to matter through processes of materialization and the iterative enfolding of phenomena into apparatuses of bodily production. The material and the discursive are mutually implicated in the dynamics of intra-activity and enfolding. Material and discursive constraints and exclusions are similarly entangled, thereby limiting the validity of analyses that attempt to determine individual effects of material or discursive factors (indeed, they misidentify their objective referents and elide important questions of responsibility). Furthermore, the conceptualization of materiality offered by agential realism makes it possible to take account of material constraints and conditions once again without reinscribing traditional empiricist assumptions concerning the transparency of knowledge practices and the givenness of the world and without falling into the analytical stalemate that simply calls for a recognition of the mediation of the world and then rests its case. The ubiquitous pronouncements proclaiming that experience of the material world is "mediated" have offered precious little guidance about how to proceed. The metaphor of mediation has for too long stood in the way of a more thoroughgoing accounting of the empirical. Incorporating some of the most important insights of poststructuralism, feminist science studies, and other critical reconsiderations of the body, of matter, and of nature, the reconceptualization of materiality offered here makes it possible to take the empirical world seriously once again in the construction and testing of theories, but this time with the understanding that the objective referent is phenomena, not the seeming "immediate givenness" of the world.

In the chapter's opening vignette, I suggest that geometrical analyses are insufficient for a thoroughgoing account of complex events such as the one described. What is the intrinsic metric in this example? What feature unambiguously defines the sense of proximity, location, distance, or scale that determines its geometry? Understanding the dynamics of this complex "trans-action"—which involves not merely the transgression of spatial and other material-discursive boundaries but a re(con)figuration of the spacetimematter manifold itself—requires topological analysis. Questions of size and shape (geometrical concerns) must be supplemented by, and reevaluated in terms of, questions of boundary, connectivity, interiority, and exteriority (topological concerns).

Analyzing the multidimensional, multiply connected, heterogeneous, geopolitical-economic-social-cultural "landscape" on the basis of geometrical considerations will not suffice. Not even if what is meant by geometry is retrofitted for postmodern sensibilities by insisting on the relative and socially constructed nature of presumably geometrical terms (e.g., scale). Nor is it sufficient to figure responsibility in terms of positionality or other efforts to locate oneself within the relevant social horizon. The inadequacy of geometrical analysis in isolation from topological considerations lies in the very nature of "construction." Spatiality is always an exclusionary process, and those exclusions are of agential significance.

For example, in contrast to some unfortunate geometrical readings of the notion of scale (whereby the nesting relationship "local $\subset$ national $\subset$ global" is presumed to hold in the absence of any critical examination), the geographer Neil Smith explicitly explores the exclusionary nature of the production of scale. He notes that "scale is produced in and through societal activity which in turn produces and is produced by geographical structures of social interaction" (Smith 1992, 62). This insight can be understood in terms of the fact that "scale" refers to a property of spatial phenomena intra-actively produced, contested, and reproduced, and furthermore that it is "an active progenitor of specific social processes" as a result of becoming enfolded into various material-discursive apparatuses of production (66). As Smith emphasizes, "it is precisely the active social connectedness of scales that is vital" (66). This "connectedness" should be understood not as linkages among preexisting nested scales but as the agential enfolding of different scales through one another (so that, for example, the different scales of individual bodies, homes, communities, regions, nations, and the global are not seen as geometrically nested in accordance with some physical notion of size but rather are understood as being intra-actively produced through one another). That is, Smith's notion of "jumping scales" can be elaborated as an element of a topological dynamics in terms of agential enfoldings that reconfigure the connectivity of the spacetimematter manifold.

Boundary transgressions are another instance where geometrical considerations will not suffice. Boundary transgressions should be equated not with the dissolution of traversed boundaries (as some authors have suggested) but with the ongoing reconfiguring of boundaries. For example, information technologies are often touted as the neutrino of the geopolitical-economic-social-cultural landscape, passing through matter as if it were transparent, innocently traversing all borders, whether those of nation-states or different computer platforms, with undiscriminating ease and disregard for obstacles

—the great democratizer, the realization of a mobility and reach that know no bounds. But information technologies do not produce a flat spacetime manifold, a level playing field; on the contrary, in some cases they exacerbate the unevenness of the distribution of material goods, further stabilizing constraints that place restrictions on the everyday lives of those who experience this so-called expansion of opportunity as a diminishing of possibilities.[31] Similarly, as Fernandes (2001) makes clear, trans/nationalism does not make the notion of the nation-state obsolete. The relationship between the local, the regional, the national, and the global is not a geometrical nesting. Local, regional, national, and global are topological matters, intra-actively produced through one another, so that an increase in the flow of information and goods across national boundaries does not in and of itself constitute the obsolescence of the nation-state.

What is needed are genealogies of the material-discursive apparatuses of production that take account of the intra-active topological dynamics that iteratively reconfigure the spacetimematter manifold. In particular, it is important that they include an analysis of the connectivity of phenomena at different scales.[32] As Ruth Wilson Gilmore points out, it is crucial to trace the "frictions of distance," to do analyses that move through the range of scales of injustice, not by pointing out similarities between one place or event and another, but by understanding how those places or events are made through one another.[33]

The topological dynamics of space, time, and matter are an agential matter and as such require an ethics of knowing and being: intra-actions have the potential to do more than participate in the constitution of the geometries of power; they open up possibilities for changes in its topology and dynamics, and as such, interventions in the manifold possibilities made available reconfigure both what will be and what will be possible. The space of possibilities does not represent a fixed event horizon within which the social location of knowers can be mapped, nor does it represent a homogeneous, fixed, uniform container of choices. Rather, the dynamics of the spacetime manifold are iteratively reworked through the inexhaustible liveliness of the manifold's material configuration, that is, the ongoing dance of agency immanent in its material configuration. The politics of identity and the politics of location, however useful, have been circumscribed by a geometrical conception of power that arrests and flattens important features of its dynamics. Perhaps what is needed is a politics of possibilities (Gilmore): ways of responsibly imagining and intervening in the configurations of power, that is, intra-actively reconfiguring spacetimematter.

SEVEN

Quantum Entanglements: Experimental Metaphysics and the Nature of Nature

The tradition in science studies is to position oneself at some remove, to reflect on the nature of scientific practice as a spectator, not a participant. Rather than holding the instruments of science in one's own hands, lighting a choice sample with one's passions, and placing the implement at one's lips to draw in the rich and penetrating aromas of scientific practice (including the finest mixtures of laboratory scents—like the unmistakable musty odor of the basement laboratory, the smell of machinery grease, noxious chemicals, and other organic and inorganic matter—and the sweet perspiration of theory and model building), allowing them to play on one's tongue and feeling the sensations pervade one's very cells, for the most part, science studies scholars, whether ethnographers, philosophers, or historians, only partake of these pleasures secondhand.[1] My project departs from science studies approaches that place science at a remove. In my account, the study of science and the study of nature go hand and hand.

This was also true for the physicist Niels Bohr. Bohr learned his epistemological lessons by doing science, not by thinking about science from outside. And conversely, epistemological, ontological, and ethical considerations were part and parcel of his practice of science. Indeed, for Bohr, these considerations are intimately connected. According to Bohr, the central lesson of quantum mechanics is that we are part of the nature that we seek to understand. And therefore a thoroughgoing consideration of the nature of nature must include a concomitant consideration of the nature of scientific practices and vice versa. In particular, Bohr argues that scientific practices must be understood as intra-actions among component parts of nature and that our ability to understand the world hinges on our taking account of the fact that our knowledge-making practices are material enactments that contribute to, and are part of, the phenomena we describe. Bohr's naturalist commitment to understanding both the nature of nature and the nature of science according to what our best scientific theories tell us plays an important role in the development of his interpretation of quantum physics.[2] The question is whether he remains faithful to this commitment or whether ultimately he allows humanist assumptions to take root to the point where a human observer winds up being foundational to the nature of nature.

Exercising my own naturalist commitment to practice science and science studies together, that is, to study nature and the study of nature as one entangled practice, I break with science studies' traditional practice of reflecting on science from outside. That is, I do not merely reflect on science, I *engage in the practice of science while addressing entangled questions about the nature of scientific practice.* In particular, in this chapter I turn my attention to a set of unresolved questions in the foundations of quantum mechanics. Having started with quantum physics, I come back around again to the problem of how to understand what it means, but this time with more refined tools in hand for doing science and science studies as a single entangled endeavor. That is, having begun the development of agential realism with the profound philosophical challenges raised by quantum physics, I return to this subject matter and ask if agential realism provides any useful insights that might help solve some of the unresolved foundational problems. I begin by continuing the task I started in chapter 3 of explicating Bohr's interpretation of quantum physics and examining closely the role that Bohr assigns to human participants in the practice of science. I argue that Bohr's reliance on human concepts, human observers, and human knowledge practices undermines his ability to offer a cogent interpretation. I then propose an interpretation that is more faithful to naturalism than Bohr's. In particular, I propose an interpretation of quantum physics based on agential realism. In summary, in this chapter I present a new scientific result: a way of interpreting quantum physics that builds on Bohr's interpretation while removing its humanist elements.

I have attempted to make this chapter accessible to readers who have little or no background in physics. The material is not easy, but not because the mathematics is difficult. In fact, there are only two different kinds of equations in this entire chapter and they entail nothing more than the mathematical operations of multiplication and addition.[3] The challenge is in following the arguments, and this takes care and sometimes more than a bit of patience, especially when the results run counter to one's intuition. The issues in the foundations of quantum mechanics are subtle and complex, and therefore it is crucial that we rigorously engage with the issues, paying careful attention to the necessary details. This is essential to any serious engagement with the questions at hand. The journey can be difficult but there are many rewards for making the effort. The foundational issues in quantum physics are fascinating and serve as a testing ground for long-standing philosophical quandaries, including some of those most central to metaphysicians, philosophers of science, and poststructuralists alike, such as the nature of identity, being, meaning, and causality. Indeed, there are riches to be found even for those who do not grasp every detail or nuance. On the other hand, the reader interested in merely being dazzled, entertained, and mystified by a quixotic sideshow of isolated facts and cutesy quirks of quantum theory will not find satisfaction here; in my opinion, there are already far too many oversimplified, confused, and glossy-eyed portrayals of quantum physics available. Indeed, there are many options available for those who would rather hang out on the sidelines than embark on the journey. I want to remind readers who may feel more comfortable traipsing about in the fields of the humanities and social sciences that poststructuralism is no walk in the park, either; one has to make a commitment to the difficult and sweaty labor required to successfully navigate that landscape. But the trip through the difficult terrain is well worth it, and even the best topological map simply doesn't capture the beauty of the embodied experience.[4]

The purposeful deployment of spatial metaphors and the theme of exploration in the previous passage are intended both sincerely and ironically. I mean to cajole, entice, and tease the hesitant traveler by using this classic metaphor of the journey to mark the adventure of scientific discovery. The path is not singular or straightforward, each step takes place on many entangled levels, the full intricacy of which will remain beyond the horizon for the reader who refuses to join the journey. I first set the scene, point out some of the main attractions, and then the ground falls out from under us . . .

PRELIMINARIES

> Of course, every theory is true, provided you suitably associate its symbols with observed quantities.
>
> —EINSTEIN, as quoted in Schrödinger, "Might Perhaps Energy Be a Merely Statistical Concept?"

Three-quarters of a century after the birth of quantum theory, central questions remain concerning its foundations. A formalism exists. The laws of classical mechanics, formalized as Newton's equations, have been supplanted by the Schrödinger equation of quantum mechanics. But the interpretative issues—questions about how to interpret the formalism—remain unresolved.

Actually, by the end of January 1926, there appeared to be two separate formulations of the laws of quantum mechanics: the matrix mechanics of

Heisenberg, Born, and Jordan (an elaboration of Heisenberg's ideas developed in the early summer of 1925) and Schrödinger's wave mechanics. At first there was competition between the two, but by the end of February 1926, Schrödinger discovered that the two formulations are mathematically equivalent "in spite of their obvious disparities in their basic assumptions, mathematical apparatus, and general tenor" (Jammer 1974, 22). Bohr embraced these formalisms as complementary: Schrödinger's formulation features the wave behavior of matter, while Heisenberg's formulation features the complementary particle behavior. Beyond these associations, however, ambiguities remain about how to interpret these mathematically equivalent formalisms. (Since there is a mathematical equivalence, physicists speak of *the* quantum formalism, in the singular.) The key point is this: "A formalism is not yet a full-fledged theory. A theory should also contain a set . . . of rules of correspondence and an explanatory principle or model" (ibid., 23). Rigorously speaking, then, quantum mechanics is not a theory but a formalism. Or, as Einstein put it when Schrödinger discussed his new ideas with him: "Of course, every theory is true, provided you suitably associate its symbols with observed quantities."[5]

And yet, despite its unresolved interpretative structure, the theory of quantum mechanics is held to be the most accurate in the history of science. How can this be? In the absence of a coherent interpretative framework, how do physicists even know how to relate what they measure with what they calculate? What is the basis for this proclaimed efficacy? How is it that a formalism has been so widely accepted by a scientific community without its interpretative structure in place? These are important questions. Let's examine what is meant by this claim.

First let us consider what it means when a physicist claims to have solved an equation. For example, take the case of Newton's equation $F = ma$. The equation is said to symbolize the following relationship: force equals mass times acceleration. That is, for a given particle of mass m, the external force F exerted on the particle provides the particle with an acceleration a given by the ratio of the force to the mass. Now, acceleration is the rate of change of velocity, which itself is the rate of change of position (making Newton's equation a second-order differential equation). If one knows the set of forces acting on a particle of a given mass m as well as the initial conditions at time t, then it is possible to solve Newton's equation to determine the trajectory of the particle, that is, how its position changes in time. In particular, since it is a second-order differential equation in time, the solution of Newton's equation requires the specification of the initial values of two

variables: the initial position and the initial momentum (momentum is mass times velocity). Newton's equation is deterministic: given the initial position and momentum (along with the set of forces and the mass of the particle), the entire trajectory of the particle is determined for all time, and its entire past and future can be calculated.

Now let's return to the case of quantum mechanics. Schrödinger's equation is also a differential equation. As in Newton's equation, Schrödinger's contains a term that represents the forces (or more precisely the related potential energies) acting on a particle of mass m, and it is necessary to indicate initial (or boundary) conditions to specify the solution. However, what one calculates is not the trajectory of a particle. Rather, one solves for the "wave function" as it varies in space and time.[6] Recall that Schrödinger's formulation attends to the wavelike behavior of matter (see chapter 3 on wave-particle duality). But these "waves" aren't waves in the same sense as water waves or sound waves. It isn't clear what's "doing the wiggling," and in fact the values of the Schrödinger wave function can be imaginary, rather than real, numbers, which means it cannot be taken literally as representing a physical quantity directly, but may be more complexly related to some physical quantity.[7] The fact that the Schrödinger equation can be solved for a host of different physical situations is all well and good, especially if you know what a wave function is. But, in fact, this is one of the foundational issues that is still unresolved. Physicists do not even agree whether the wave function tells about what we can know about a physical system or what exists.[8] Different interpretations of quantum mechanics understand the wave function differently.

When it comes to discussing the interpretational issues, a host of possibilities have been advanced. But when it comes to doing calculations, there is an instrumental agreement to use the so-called Copenhagen interpretation. What physicists generally mean when they invoke the "standard" (Copenhagen) interpretation on this count is that they are taking the (absolute square magnitude of the) wave function to represent the probability (density) that a particle of mass m will be found in a given position at a given time. In essence, the point is this: it is accepted that the Schrödinger equation allows one to calculate all that it is possible to know about a given physical situation, which is not a precise trajectory as in Newtonian physics, but the specification of the probability that a particle will be found at some position x when it is measured at some time t. It is this stance that plays itself out so efficaciously for many situations. For example, it is possible to use the wave function to calculate the discrete set of energy states occupied by electrons in an atom and to test these values against experimental measurements. (When electrons "jump" from a higher energy level to a lower one, they emit a photon, a particle of light, with a frequency, or color, corresponding to the difference in energy between levels. Each atom, having a different distribution of possible energy levels, has a unique spectrum. "Spectroscopic data" can be compared with the predictions based on the calculation of energy levels.) To date, the quantum mechanical formalism accurately accounts for the observed spectroscopic data, and many other physical quantities as well.

Indeed, the theory of quantum mechanics has proved enormously powerful in its ability to account for phenomena ranging from the smallest particles of matter to questions about the stability of cosmological objects like black holes, from laser pulses that change shape and state of polarization on the scale of a few femtoseconds, a tiny fraction of time, to events that reach back to the beginning of the universe. Quantum physics has proved to be enormously fertile, spawning a plethora of new fields of inquiry including quantum field theory, elementary particle physics, condensed matter physics, and cosmology. The empirical efficacy of quantum physics is also evidenced in the technologies it has spawned, from semiconductors to lasers, to medical imaging technologies, such as MRIS and PET scans. As one science writer notes, "By some estimates, 30 percent of the United States' gross national product is said to derive from technologies based on quantum theory. Without the insights provided by quantum mechanics, there would be no cell phones, no CD players, no portable computers. Quantum mechanics is not a branch of physics; it is physics" (Folger 2001).

However, when the interpretational issues are examined in detail, it becomes clear that the standard Copenhagen "interpretation" is not a coherent interpretation at all. Rather, it is a pastiche of different elements, a partially negotiated and indeterminate combination or superposition of contributions from leading physicists who worked on the founding of quantum mechanics, rather than a coherent account.[9] Considering the enormous productivity of the quantum formalism, it is perhaps not surprising that the overwhelming majority of physicists have focused on, and continue to focus on, the computational successes of the formalism while bracketing the unresolved interpretational issues. Significantly, computational success was an especially propitious emphasis for theoretical physicists in the United States struggling to establish themselves in the physics profession during the 1930s, when before the advent of quantum mechanics, physics in the United States had meant experimental physics—period. It was during the same period that the

center of physics shifted westward across the Atlantic, and questions of interpretation that occupied the attention of some European theoretical physicists, most notably Bohr and Einstein, were given short shrift as the pragmatic American style, with its emphasis on "getting the numbers out," began to define contemporary physics culture worldwide.[10]

Discussion of the interpretational issues, which were a lightning rod for the intellectual energies of Bohr and Einstein, reached their pinnacle in 1935. They were not resolved but rather for decades were consigned to the realm of the "merely philosophical." Even the astonishing findings of John Bell during the 1960s and subsequent experiments in the 1980s that provided an *empirical* handle for resolving some of the most profound *metaphysical* issues in quantum physics, the very ones highlighted in the Bohr-Einstein debates, were given scant attention in the physics community (Ballantine 1987). Only in the past decade have things begun to change. Two key factors have contributed to this shift: technological progress in experimental physics that has enabled the realization of the classic "thought" experiments of Einstein, Bohr, Schrödinger, and others; and excitement about the new field of quantum information theory, which has important technological implications (see chapter 8). In particular, during the past decade it has become clear that the so-called merely philosophical issues have far-reaching consequences for practical innovations such as quantum computing, quantum cryptography, and quantum teleportation. These quantum information theory projects are still on the drawing board, but they promise to revolutionize the computing, finance, national security, and defense industries, for starters, and development efforts are receiving millions of dollars of R & D support. So as it turns out, several U.S. government agencies, including the National Security Agency (NSA), Defense Advanced Research Projects Agency (DARPA), National Reconnaissance Office (NRO), Advanced Research and Development Agency (ARDA), National Aeronautics and Space Administration (NASA), National Institute of Standards and Technology (NIST), Department of Energy (DOE), and the Army, Navy, and Air Force are now interested in such "merely philosophical" issues as quantum entanglement, a notion that lies at the heart of the interpretative issues in quantum mechanics.

This chapter is organized as follows. I begin, in the next section, with an overview of some of the paradoxes and quandaries that have plagued quantum mechanics since its founding three-quarters of a century ago, including the important contributions of various *gedanken*, or thought, experiments. I then discuss a new domain of investigation—experimental meta/physics—made possible by new technological developments that allow actual laboratory realizations of the classic thought experiments. Next I consider some serious objections and limitations of Bohr's interpretation, and dispel some common misunderstandings. In the final section, I consider the possibility that agential realism is the basis for a new interpretation, examine its potential for resolving certain long-standing paradoxes in the field, and compare it to some of the newer interpretations that have recently been proposed.

PHYSICISTS AND FELINES: FOUNDATIONAL ISSUES IN QUANTUM PHYSICS

> It is all quite mysterious. And the more you look at it the more mysterious it seems.
>
> —FEYNMAN ET AL., *The Feynman Lectures on Physics*

> Anyone who is not shocked by quantum theory has not understood it.
>
> —BOHR, *The Philosophical Writings of Niels Bohr*

Quantum mechanics poses some of the most thoroughgoing challenges to our common-sense worldview. This section presents some of the key foundational issues in quantum mechanics. It is divided into four subsections:

1 Quantum Variations on a Theme by Thomas Young: Superpositions, Mixtures, and "Which-Path"–Interference Complementarity (one-particle superpositions)
2 The EPR Paradox: On the Nature of Physical Reality (two-particle entanglements)
3 Schrödinger's Cat Paradox (many-particle entanglement, macroscopic objects)
4 The Problem of Measurement (many-particle entanglement, macroscopic devices)

1 QUANTUM VARIATIONS ON A THEME BY THOMAS YOUNG: SUPERPOSITIONS, MIXTURES, AND "WHICH-PATH" –INTERFERENCE COMPLEMENTARITY

> We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by 'explaining' how it works. We will just tell you how it works. In telling you how it works we will have told you about the basic peculiarities of all of quantum mechanics.
>
> —FEYNMAN ET AL., *The Feynman Lectures on Physics*

Superpositions are said to embody the mysteries of quantum mechanics.[11] So we begin our investigation of the foundational issues by turning our attention to superpositions. What are they? Where do they come from? How do they arise in the quantum mechanical formalism? And last but not least, what is their significance, and how are we to understand them?

As mentioned earlier, the Schrödinger equation (SE) is said to represent the wave behavior of particles. Recall that waves are not entities but disturbances extended in space—think of a wave at the beach. Unlike particles, waves can be superimposed on one another. For example, when two ocean waves overlap, the amplitude of the resultant wave is the combined amplitudes of the component waves: the amplitude of one wave is added to the amplitude of the other wave, and the result is a wave with their combined amplitude (see chapter 2). The resultant wave is said to be a linear combination or a superposition of the component waves. Like water waves, Schrödinger wave functions can also be added together to form superpositions. For example, let ψ_1 and ψ_2 (the Greek letter ψ, psi, is conventionally used to represent the wave function) represent two solutions to the SE for a particular situation.[12] At first it may seem odd that there would be more than one solution to a given problem but this is often the case. (It's easiest to get a sense of what it means for there to be more than one solution by looking at specific examples, which we'll do next.) There is a mathematical theorem that says that if both ψ_1 and ψ_2 are solutions to the SE, then any arbitrary linear combination of the two solutions ψ_1 and ψ_2 is also a solution of the SE. In other words, if both ψ_1 and ψ_2 are solutions, then if we multiply each of the individual solutions by an arbitrary (complex) number and add them together, the sum will also be a solution

$$\psi = a\,\psi_1 + b\,\psi_2 \qquad (7.1)$$

as long as the coefficients are appropriately normalized (i.e., they are related as follows: $|a|^2 + |b|^2 = 1$. The reason for this constraint is explained hereafter). (Notice that this equation is a generalization of the case we talked about with water waves, but instead of simply adding each of the component waves, we're allowing each component to be multiplied by a number first and then we add them together. In the case where a = b = 1 the equation reduces to a simple addition of the component waves.) That is, superpositions of individual solutions are viable wave functions. Mathematically speaking, this is due to the fact that the SE is a linear equation. Hence the very existence of superpositions is a feature of the wave behavior of matter.

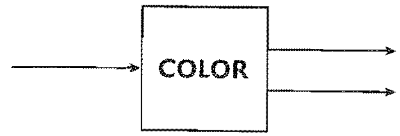
Let's consider some examples. Suppose we want to measure some property of a particle; let's call this property "color." And suppose that every time we measure the color of a particle, any particle, we always get one of two possible values—"red" or "green." Any system of this kind—one in which the property measured (i.e., color) can take on one of two possible values—is called a two-state system. (If there are N possible values, it is an N-state system.) A two-state system has two characteristic solutions, also called *eigenfunctions* or *eigenstates* (*eigen* is German for characteristic). We'll call one eigenstate ψ_r and the other one ψ_g. If we measure the property called "color" of eigenfunction ψ_r, we find that the answer is "red," and correspondingly if we measure the color of ψ_g, we find that the answer is "green." The measured values, "green" and "red," are called the corresponding *eigenvalues*. The linearity of the SE means that any arbitrary linear combination of ψ_r and ψ_g is also a solution; that is, it is also a physically allowed state. We can represent this superposition as follows:

$$\psi = a\,\psi_r + b\,\psi_g, \text{ where a and b are (complex) numbers and } |a|^2 + |b|^2 = 1 \quad (7.2)$$

That is, for any two-state system, the most general solution to the SE is of this form (i.e., a linear combination of the two eigenfunctions). (And, as you may have guessed, the most general solution for an N-state system is a linear combination of N terms, namely, the N-eigenfunctions.) Indeed, since the coefficients a and b are any (complex) numbers (as long as the sum of the [complex] squares is equal to 1, i.e., $|a|^2 + |b|^2 = 1$), there are an infinite number of allowed or possible physical states. (The reason for this constraint on the coefficients will become clear later.) On the other hand, there are two special states: the two eigenstates ψ_r and ψ_g. (The first eigenstate, ψ_r, is a special case of the general solution where $a = 1$ and $b = 0$. And the other eigenstate, ψ_g, is a special case of the general solution where $a = 0$ and $b = 1$.) Eigenstates are clearly special states of the system. I will have more to say about their special nature later.

So we've learned that superpositions exist mathematically; they are the result of the linearity of the SE. But what do superpositions represent? How are we to understand them physically?

To get a handle on this, let's consider what happens if we measure the color of a superposition of eigenstates. Suppose we make an instrument for measuring the property color. Figure 17 shows the schematic for such a device. For our purposes, a color-measuring device is simply a black box with one input and two possible outputs. We needn't concern ourselves with the guts of the black box. All we need to know is that it sorts particles by color: if we send in particles from the left, the color of the particle is measured inside the box and the particle exits on the right through the top slit if the color measured is red or through the bottom one if the color measured is green.



17 Color-measuring device. *Illustration by Nicolle Rager Fuller for the author.*

Let's first test the device using the eigenstates. If we send 100 particles represented by the eigenstate ψ_r into the device, then all 100 particles will come out of the top output, indicating that they all have eigenvalue red. Likewise, if 100 particles represented by the eigenstate ψ_g are sent into the device, then all 100 particles will come out of the bottom output, indicating they all have eigenvalue green. Not only have we shown by these simple experiments that our device is working correctly, but in retrospect we will see that they also indicate that the special nature of eigenstates is that they *are states with definite characteristics for the property in question*.

The best way to appreciate this fact is by considering a contrasting case in which the wave function is not one of the eigenstates. Suppose that we send in 100 particles represented by the superposition

$$\psi = \sqrt{\frac{1}{4}}\,\psi_r + \sqrt{\frac{3}{4}}\,\psi_g \quad (7.3)$$

which is one of an innumerable number of superpositions satisfying the requirement that $|a|^2 + |b|^2 = 1$, where in this case $a = \sqrt{\frac{1}{4}}$ and $b = \sqrt{\frac{3}{4}}$ (which indeed satisfies the constraint equation: $\left|\sqrt{\frac{1}{4}}\right|^2 + \left|\sqrt{\frac{3}{4}}\right|^2 = \frac{1}{4} + \frac{3}{4} = 1$). What we find in this case is that, to within experimental error, 1/4 of the 100 particles, or 25 particles, come out of the top output, indicating a red eigenvalue, and 3/4 of the 100 particles, or 75 particles, come out of the bottom output, indicating a green eigenvalue. Another way to state the outcome of this experiment is that for any given particle there is a 25% chance that it will be found with color red and a 75% chance that it will be found with color green. Now we can make sense of the constraint on the coefficients. The constraint equation, $|a|^2 + |b|^2 = 1$, guarantees that for each measurement the outcome will be one of the allowed eigenvalues. That is, the constraint equation reads: the probability that red occurs plus the probability that green occurs equals 100%. Each measurement will yield red or green; there are no other possible outcomes.

On the basis of this experiment, a reasonable hypothesis might be that superpositions represent a mixture of particles with different colors. In what follows, we'll test this hypothesis further.

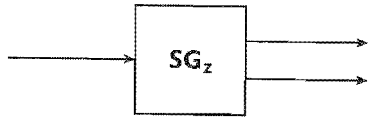
Let's progressively make this example more concrete and representative of actual cases one encounters in physics. Instead of "color," suppose the characteristic we want to measure is "spin" and that the values obtained are either "up" or "down" rather than "red" and "green."[13] There's nothing more complicated about this system than the one we just discussed. This is also a two-state system, and every measurement of "spin" produces a value of either "up" or "down," symbolized by ψ_u and ψ_d, respectively. That is, ψ_u and ψ_d represent the two possible eigenstates of the system with eigenvalues "up" and "down," respectively. The most general solution for this system is

$$\psi = a\,\psi_u + b\,\psi_d \qquad (7.4)$$

where a and b are (complex) numbers and $|a|^2 + |b|^2 = 1$. (Notice that $\psi = \psi_u$ when $a = 1$, $b = 0$; and $\psi = \psi_d$ when $a = 0$, $b = 1$. That is, the most general solution includes both eigenstates and all possible superposition states.)

Now, spin is actually what is called a vector quantity. Classically speaking, you can think of spin as a vector or arrow pointing in a particular direction in space. The direction of the arrow indicates the direction in space of the spin axis (the axis of rotation), and the size of the arrow indicates how fast the object is spinning. In general, we can specify a vector by saying what the three spin components are along the x-, y-, and z-directions. So spin is characterized by its three components; call them S_x, S_y, and S_z.

A device that can be used to measure spin values along a particular direction in space is a Stern-Gerlach apparatus, SG for short.[14] The SG device has an inhomogeneous magnetic field oriented along a particular direction. We can orient the magnetic field along any of the three directions: the x-direction, the y-direction, or the z-direction. When the magnetic field is oriented along the z-direction, we indicate this by the shorthand SG_z, and similarly for SG_x and SG_y. SG_z measures spin in the z-direction, that is, S_z, and similarly for the other two components. The device discriminates between the "up" and "down" values by splitting a beam of particles into two traces depending on their spin values along that axis: some particles are deflected upward by the magnet field, and some are deflected downward. The ones deflected upward have a spin eigenvalue of "up," and their corresponding eigenstates are symbolized as ψ_u. Likewise, the ones deflected downward have a spin eigenvalue of "down," and their corresponding eigenstates are symbolized as ψ_d. So the SG device looks very similar to the color-measuring device. An SG_z device, for example, has one input and two outputs, with the



18 Spin-measuring device. This Stern-Gerlach device measures spin in the z-direction. *Illustration by Nicolle Rager Fuller for the author.*

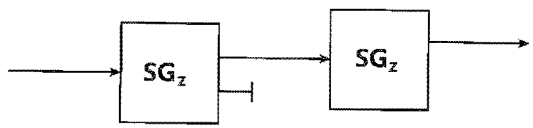
top output collecting particles with spin eigenvalue up and the bottom output collecting particles with spin eigenvalue down (see figure 18).

Now let's use these devices to do some measurements. What happens if we send a beam of particles represented by the eigenstate ψ_u into an SG_z device? We find that they all emerge from the top output. Similarly, if the incoming beam of particles is represented by the eigenstate ψ_d they all emerge from the bottom output. Now suppose we shoot a beam of particles represented by the following superposition state into the SG_z device

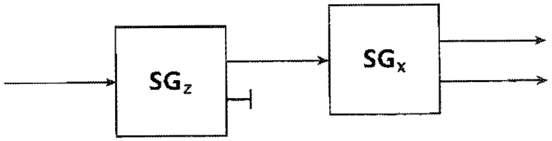
$$\psi = \sqrt{\frac{1}{2}}\,\psi_u + \sqrt{\frac{1}{2}}\,\psi_d \qquad (7.5)$$

If we direct this beam into the SG_z device, 1/2 of all the particles emerge through the top, and 1/2 emerge through the bottom (because the square magnitudes of the coefficients are both 1/2). To be concrete, if we send in 200 particles, we'd find 100 particles with measured eigenvalue up in the z-direction and 100 with measured eigenvalue down in the z-direction.[15] Now suppose we block the bottom beam of the output of the SG_z device and send the top beam into a second SG_z device (figure 19). What happens is just what we'd expect: all the particles that emerge through the top output of the first SG_z and head into the second one emerge through the top of the second device, indicating that all the emerging particles have measured eigenvalues up in the z-direction. This exercise simply confirms the consistency of the results (and the fact that the device is doing its job).

Now let's replace the second SG_z device with an SG_x device (figure 20).



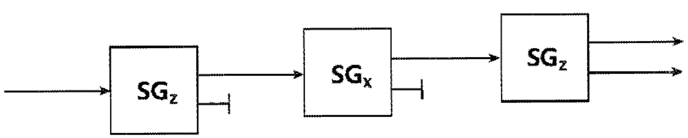
19 Experiment 1. *Illustration by Nicolle Rager Fuller for the author.*



20 Experiment 2. *Illustration by Nicolle Rager Fuller for the author.*

Starting out with 200 particles in the superposition specified earlier and sending them into the SG_z device yields 100 particles that emerge from the top output with measured eigenvalue up in the z-direction, which are then passed into an SG_x device, whereupon 50 of the particles emerge from the top with measured eigenvalue up in the x-direction and 50 from the bottom with measured eigenvalue down in the x-direction. There seems to be nothing remarkable about this result. We might simply conclude that the particles that emerge from the top output of the second spin-measuring device have spin-up in the z-direction and spin-up in the x-direction, and that the ones that emerge from the bottom output have spin-up in the z-direction and spin-down in the x-direction. These results are all consistent with our initial hypothesis that a superposition represents a mixture of particles with different spins and the devices are simply sorting them out. So far, so good.

Now let's try a slightly more complex experiment, one with three devices (figure 21).[16] Suppose that we add a third spin-measuring device—another device that measures spin in the z-direction—to the last experiment. Now, you might think this is rather silly, because we already know the z component of the spins of the particles from the first SG_z measurement, and so the third one won't tell us anything new. Indeed, you might suspect that if the top beam, for example, from the SG_x device is directed into the input of the final SG_z device, then all 50 particles would emerge from the top output, since the ones that had spin-down in the z-direction were blocked off after the first measurement of S_z. However, this intuition proves to be wrong! If we perform the experiment, what we find is that 1/2 of the particles, 25 of



21 Experiment 3. *Illustration by Nicolle Rager Fuller for the author.*

them, emerge from the top output of the last device, and an equal number, 25, emerge from the bottom output. But how can this be?

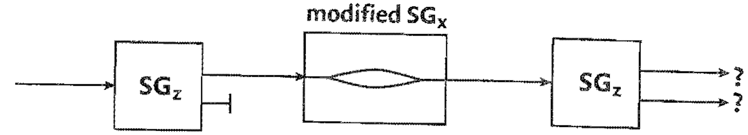
Everything seemed just fine without the SG_x device in the middle (see the earlier experiment with two SG_z devices in a row). But something seems to have gone awry when we included the SG_x device. It seems as though the SG_x device did something to "mess up" the second measurement of spin in the z-direction. How can we understand this result? Did the measurement of the spin value in the x-direction somehow disturb the value of the particle's spin in the z-direction?

It turns out that what we are witnessing here is the result of an uncertainty or indeterminacy principle for spin components. Indeed, one can use the quantum mechanical formalism to derive an expression that indicates that it is not possible to determine more than one of the three components of the spin-vector at the same time.[17] According to Heisenberg, the reason for this is that the three components are not simultaneously knowable, but in Bohr's account it is because they do not have simultaneously determinate values. It is important to distinguish between these two nonequivalent positions: uncertainty and indeterminacy. Heisenberg's uncertainty principle is an epistemic principle: it favors the notion that measurements disturb existing values, thereby placing a limit on our knowledge of the situation. By contrast, Bohr's indeterminacy principle (alias the quantitative expression of complementarity—see hereafter) is an ontic principle: the point is not that measurements disturb preexisting values of inherent properties but that properties are only determinate given the existence of particular material arrangements that give definition to the corresponding concept in question. In the absence of such conditions, the corresponding properties do not have determinate values. And the determinateness of one set of properties materially precludes the determinateness of a complementary set. (See chapter 3 for a detailed discussion of Bohr's interpretation and for a discussion of the important differences between Heisenberg's uncertainty principle and Bohr's indeterminacy principle. See also the discussion hereafter for further clarifications. Note that this chapter assumes prior knowledge of the contents of chapters 3 and 4.) I will consider each possibility in turn.

According to Heisenberg, a precise measurement of the x-component of the spin disturbs the particle, changing the previous value of spin in the z-direction. Hence, once we measure the x-component, we shouldn't expect to find the same results for the z-component as we measured previously (that is, before measuring the x-component). That is, the fact that the x-component is measured in between two measurements of the z-component matters. This account fits nicely with a conventional (Newtonian) view of metaphysics, whereby there are individual objects with individually determinate properties, and measurements reveal the preexisting values of particular physical quantities. However, unlike the case of Newtonian physics, Heisenberg's uncertainty principle tells us that there are limits to determining these preexisting values because measurements necessarily introduce uncontrollable disturbances. So we are *not* justified in concluding, as we were tempted to conclude after Experiment 2 (see figure 20), that the particles that emerge from the top output of the second spin-measuring device have spin-up in the z-direction and spin-up in the x-direction, and that the ones that emerge from the bottom output have spin-up in the z-direction and spin-down in the x-direction. But this result also doesn't clarify what we are to make of superpositions. How can we understand expressions like equation (7.5)? What does it say about the nature of the properties of the particles being measured and the nature of measurement? How can we reconcile this with a classical metaphysics that assumes that objects have determinate properties with definite values? Do superpositions represent our ignorance? Do wave functions represent what we can know rather than what exists? (In the case of Newtonian physics we might assume these are the same.)

Let's add one more experiment to try to get at this issue before going on to consider Bohr's interpretation. Suppose that we make a modified SG_x device that allows the possibility of recombining the separated up and down beams before going on to the next detector.[18] (We can achieve this by using an appropriate arrangement of magnets.) The overall experimental configuration is basically the same as that used in Experiment #3, but now the SG_x device is replaced by a modified SG_x device (figure 22).

If the downward directed beam in the modified SG_x device is blocked when the beams are separated and only the top beam is allowed to pass through the output of the device and into the input of the SG_z device, then the same result as in Experiment #3 will obtain. However, if the beams are allowed to recombine, that is, if neither path is blocked, before the particles exit the modified SG_x device and pass into the SG_z device, then all particles will exit from the top of the final SG_z device, as in Experiment #1—just as if the modified SG_x device were not there! How can this be? Weren't the beams separated just as in Experiment #3 (before being recombined)? What difference does the recombining make? Doesn't the measurement that separates up and down in the x-direction disturb the spin in the z-direction just as much, whether or not one of the paths is ultimately blocked, that is, whether or not the beams are allowed to recombine? How is it possible to (exactly) undo the disturbance by recombining the beams? The results of this experiment seem to indicate that what is at issue is not a matter of disturbance after all.[19] The further we explore, the more questions seem to arise concerning the nature of measurement and the nature of nature.



22 Experiment 4. *Illustration by Nicolle Rager Fuller for the author.*

Let's see if we do any better following the logic of Bohr's interpretation. Bohr's account is less intuitive because it entails a radical departure from classical metaphysics. According to Bohr, quantum mechanics tells us that it is not correct to think of spin as a vector with a given magnitude pointing in a particular direction in space because this would be to assume that the three components of spin are simultaneously determinate. Rather, in Bohr's account, quantities are only determinate if the appropriate conditions for their measurement exist. In particular, for the case in point, a determinate value exists for the z-component of the spin if a device for measuring this property is in place. In the absence of such a device, the value of the corresponding property will not be determinate.

More specifically, when an SG_z device is in place, the specific material arrangement (not the will of the experimenter) enacts a cut between the "object of observation" and the "measuring device" such that the boundaries and properties in question become determinate. In particular, with the SG_z device in place, the notion of spin in the z-direction becomes meaningful, and the value of the corresponding property becomes definite. In the absence of such a device, the concept of spin in the z-direction is meaningless, and there is no fact of the matter about the boundaries and properties of the object.[20]

The results of Experiment #3 can then be understood as follows. When the first SG_z device is in place, S_z is determinate. But when the SG_x device is put in place for the second measurement, the x-component of spin becomes determinate, and the z-component is no longer determinate (i.e., there is no fact of the matter concerning its value). Hence we can now understand how it is possible that when S_z is measured again, following the S_x measurement, that the particles emerge from both outputs. The point is that the middle measurement of S_x matters because when the x-component is measured, the z-component is no longer determinate. Consequently when the final SG_z device is put in place, the z-component becomes determinate, but this is just after it was indeterminate, so there is no reason to have more up eigenvalues than down ones. We were also able to reconcile this result with Heisenberg's interpretation. The question is how does Bohr's interpretation stand up to Experiment #4 (which seems inexplicable à la Heisenberg)?

Can we make sense of the results of Experiment #4 using Bohr's interpretation? According to Bohr, the determinate value of the z-component of spin that we measure with an SG_z device, for example, is the result of the *intra-action* of the particle with the device; that is, the property is a characteristic of the *phenomenon* and not some preexisting measurement-independent object. In the case where one of the beams of the modified SG_x device is blocked, say the bottom one, the device will serve as an appropriate apparatus for measuring the x-component of spin. In this case, the x-component of the spin will be determinate, and the value will be definite—either up or down. When the z-component of spin is subsequently measured, it will thus be indeterminate. Hence we will get the same result as in Experiment #3. On the other hand, suppose that we don't block either beam. In this case, the device is not appropriate for measuring the x-component of the spin and it remains indeterminate while the z-component remains determinate. Hence, we get the same result as Experiment #1 (just as if the modified SGx device weren't there). So Bohr's interpretation seems to be able to account for the entirely unexpected results of Experiment #4. On the other hand, it is not obvious how to reconcile the results of Experiment #4 with Heisenberg's interpretation.

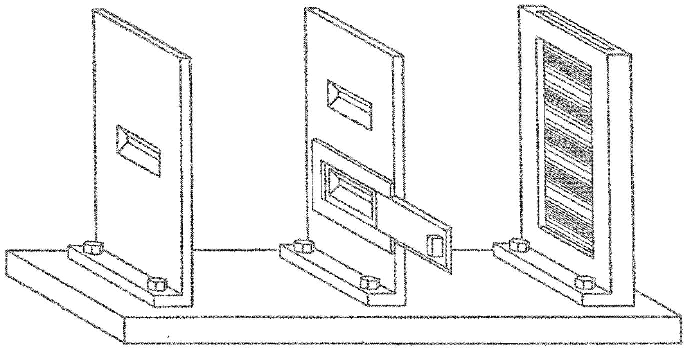
There are several important points to take from these experiments. First of all, the results are consistent with Bohr's interpretation that devices don't disclose preexisting values but rather that it is the specific material configuration that gives definition to the notion of the property in question, enacts a cut between the "object" and the "measuring instrument," and produces determinate values for the corresponding measured quantity, leaving the complementary quantities indeterminate. Which is not to say that human observers determine the results, the data doesn't come out however we want, but rather the specific nature of the material arrangement of the apparatus is responsible for the specifics of the enactment of the cut. That is, upon measurement we always find one of the allowed eigenvalues—that is, a definite value—for the quantity being measured. In recognition of this important point, physicists say that upon measurement each particle is "in" one of the allowed eigenstates (of the property in question as defined by the device). This point also goes to the consistency in the results of experiment, that is, the fact that even though measurements do not disclose preexisting values, they are not some arbitrary playing around, but rather definite, consistent, and reproducible values are obtained.[21] In conclusion then, the last two experiments make it clear that our initial hypothesis concerning what superpositions represent is wrong: superpositions do *not* represent mixtures of particles with determinate properties. Rather, *superpositions represent ontologically indeterminate states*—states with no determinate fact of the matter concerning the property in question.

Let's look at the important difference between superpositions and mixtures in more detail. Technically speaking, a *mixture* refers to a collection or ensemble of particles, each with a determinate value of the property in question, such that the state of any given particle is determinate but unknown. In particular, in a mixture, each particle is represented by a determinate eigenstate. Mixtures are often described statistically, but significantly the use of probabilities in this case is not connected with quantum indeterminacy but simply the fact that the value of a property for a given particle is unknown. That is, the use of statistics marks our ignorance: each particle has properties with determinate properties, but we may be uncertain about the values of particular properties for any given particle.

By contrast, *superpositions* embody quantum indeterminacy. If we shoot a beam of particles represented by a superposition of ψ_u and ψ_d eigenstates into an SG_z device, our inability to predict which particles will emerge with eigenvalue "up" and which with eigenvalue "down" is not due to our ignorance concerning a state with determinate values of S_z but rather because the values are themselves indeterminate before their measurement. In this case, the use of probabilities is intrinsic to the nature of quantum phenomena.[22]

Significantly, superpositions and mixtures are physically distinguishable: they leave different traces. Superpositions allow for interference effects, but mixtures do not. To see this, let's consider the canonical two-slit experiment (see chapter 3). The apparatus consists of a source, a diaphragm with two slits, and a screen (figure 23).

It is well known that under appropriate conditions a source, emitting either light or matter, aimed at the diaphragm will produce marks on the screen in the form of an interference pattern. This experiment demonstrating the wave nature of matter has become emblematic of quantum physics. As the earlier quote by Feynman suggests, the two-slit experiment can be used to explore the most fundamental issues in quantum mechanics. It's

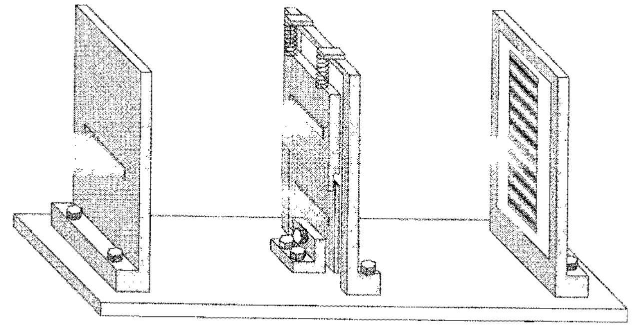


23 Two-slit experiment (as sketched by Bohr). The screen shows the characteristic interference pattern—bands of dark and light (i.e., areas of alternating low and high intensity). (Note: The slider allows the experimenter to close off the bottom slit if desired. For our purposes, the slider remains open.) *Image by Niels Bohr, cropped from diagram in Niels Bohr,* Atomic Physics and Human Knowledge, *vol. 2 (1963), 48. Reprinted with permission of Ox Bow Press, Woodbridge, Connecticut.*

one thing for light (or other kinds of waves) to exhibit an interference pattern, but it's quite another thing when it comes to material particles. This is because waves interfere with one another, that is, two or more wave disturbances can exist at a given point in space and the resultant disturbance is the sum of the amplitudes of each of the component disturbances. In other words, waves can form superpositions. But what about particles? Unlike waves, particles are localized entities, and only one particle can exist at any given point in space at a time. So how is it possible to have an interference pattern in this case? What does it mean to have a superposition of particle states?

It is important to note that in the two-slit experiment an interference pattern is produced even if the particles go through the apparatus one at a time. How can this be? Surely we'd expect each particle to travel through either the top slit or the bottom slit. We could in fact design an experiment to detect which slit each particle goes through on its way to the screen. One way to do this would be to suspend the diaphragm with (one or both of) the two slits on a spring (as suggested by Bohr) (figure 24). The idea is that this modification would allow us to detect which slit each particle passes through by watching for the displacement of the diaphragm with the upper slit.

The suggestion of using a two-slit arrangement with a movable diaphragm was originally proposed by Einstein in an attempt to circumvent the



24 Two-slit experiment with "which-slit" detector. Bohr argues that with a movable diaphragm, the interference pattern disappears and a scatter pattern is found, which is characteristic of particle behavior. *From P. Bertet et al., "A Complementarity Experiment with an Interferometer at the Quantum-Classical Boundary,"* Nature *411 (2001): 167, figure 1. Reprinted with permission of Macmillan Publishers Ltd.*

uncertainty principle and thereby show the incompleteness of quantum theory. His gedanken experiment—commonly referred to as the "recoiling slit" experiment—is a variation on the one we've been discussing. Einstein argued that, by using such a device, it would be possible to measure the momentum transfer between the particle and the movable diaphragm—that is, the disturbance the particle suffers as a result of the measurement—and hence know both its momentum and position in contradiction with the uncertainty principle. Bohr responded to Einstein's challenge by pointing to a flaw in his reasoning, arguing that it was not possible to have it both ways at once (both which-slit information and an interference pattern) and that the recoiling-slit arrangement would destroy the interference pattern. In Bohr's account, there is a necessary trade-off between which-path information and interference, that is, between particle and wave behavior, respectively. Bohr refers to this as wave-particle complementarity. Currently, it is more commonly referred to as "which-path"–interference complementarity (see the section on experimental evidence later in the chapter).[23] The point is that if we introduce an experimental arrangement that allows us to meaningfully ask and answer a question that presumes the particle-like nature of the object of investigation—such as which slit it passes through—then we find particle-like behavior and no interference pattern. For Bohr, there's nothing mysterious about wave-particle complementarity; it's simply a matter of *the material specificity of the experimental arrangement that gives meaning to* *certain classical variables to the exclusion of others, enacts a specific cut between the object and the agencies of observation, and produces a determinate value of the corresponding property*. Bohr's argument ultimately won the day (though the nature of his argument has been misunderstood, as discussed hereafter). Indeed, Bohr's account has become canonical in quantum physics despite the fact that the experiment was not performed (and there was no expectation that it would ever actually be performed) until the 1990s. Einstein didn't give up, however (and I will discuss another of his attempts in the next subsection).

Let's examine the corresponding wave functions for the fixed and movable two-slit experiments. First, suppose we have a two-slit apparatus in place that can provide a definite answer to the question of which slit each particle goes through on its way to the screen, such as the one with the movable diaphragm. Let's label each particle according to whether it traverses the top slit (ψ_t) or the bottom slit (ψ_b). In such a case, we have a mixture of particles, some with wave function $\psi = \psi_t$ and some with $\psi = \psi_b$, and the distribution pattern found on the screen is the sum of the individual distribution patterns, one for the particles going through the top slit, the other for the particles going through the bottom slit. In particular, there is no superposition and no interference pattern is observed.

By contrast, suppose we have a two-slit apparatus in place with a fixed diaphragm. In this case there is no determinate sense of the notion of "which-slit," and no determinate which-slit value exists. The wave function for this state is a superposition of the two eigenstates:

$$\psi = a\psi_t + b\psi_b, \text{ where } a \text{ and } b \text{ are nonzero} \qquad (7.6)$$

This wave function symbolizes a particle with indeterminate "which-slit" value. It is important to realize that in the absence of an experimental arrangement that gives meaning to the notion of "which-slit"—that is, an experimental arrangement that makes it possible to determine which slit a particle goes through (e.g., one with the slits placed on a movable diaphragm)—this information is not just unknown; it is *ontologically indeterminate*. It is not that we have a mixture of particles, some that go through the top slit and some that go through the bottom slit, as in the case of the apparatus with a movable which-slit detector, but rather the point is that in the fixed diaphragm case there is no fact of the matter about which slit a particle passes through. The probabilistic nature of the result is rooted in ontological indeterminacy and not classical ignorance. The resulting distribution of particles on the screen forms an interference pattern. This is to be contrasted with the distribution found in the case of an apparatus with a

movable which-slit detector, which does not exhibit interference fringes. The point is that superpositions exhibit interference patterns and mixtures do not.[24] Indeed, this is a general feature of quantum mechanics: *an interference pattern is the mark of a superposition*.[25]

In summary, superpositions are a fundamental feature of the quantum world. A mixture is physically distinguishable from a superposition: they leave different objective traces. An interference pattern is an objective mark of a superposition. Mixtures do not produce interference patterns. In the world of classical physics there are mixtures of particles but no superpositions. Superpositions challenge our classical metaphysical view of the world. A superposition or interference pattern made of particle traces is a distinctive mark of quantum behavior.

2 THE EPR PARADOX: ON THE NATURE OF PHYSICAL REALITY

In 1935, Einstein, Podolsky, and Rosen (EPR) published a paper that dealt with nothing less than the nature of physical reality and the nature of a viable physical theory. These deeply philosophical topics are rather unusual fare for a paper that appears in a physics journal. The brief article calls into question the viability of the theory of quantum mechanics, concluding that the theory is incomplete, unable to account for the full nature of physical reality. The EPR argument isn't based on a new experimental finding; rather, the authors propose a thought experiment that they claim can be used to circumvent the uncertainty principle, and they argue that that being the case, the theory of quantum mechanics is inadequate to the task of describing physical reality. In particular, the authors claimed that they had devised a way to simultaneously determine the position and momentum of a system without in any way disturbing it. Consequently, they argue that it follows that these properties are elements of physical reality, and since the theory cannot account for them, it is incomplete.

> Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory*. . . . *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity*. (Einstein, Podolsky, and Rosen 1935, 138; italics in original)

The essence of their argument is as follows. Consider two independent systems, call them A and B, that interact with each other for a finite period of time. During this period of time, the states become correlated with each other. The authors point to this "correlation" as the basis of their claim that they can deduce the properties of one system, say B, by performing measurements on the other one, system A.[26] A key point in their argument is that all measurements performed on A take place only after A and B have finished interacting with each other. "Since at the time of measurement the two systems no longer interact," the authors reason that "no real change can take place in the second system [B] in consequence of anything that may be done on the first system [A]" (Einstein, Podolsky, and Rosen 1935, 140).[27] By their account they have thereby devised a way to deduce the values of two complementary variables, say the position and momentum, of system B, by performing measurements only on system A. As such they argue that they have circumvented the uncertainty principle, since they have determined these values "without in any way disturbing the second system" (140). They therefore conclude that the properties of system B must correspond to elements of physical reality, and since the theory does not provide a way to account for them, it must be incomplete.

The crux of the EPR paper is the correlation between A and B. In an important sense the core issue is precisely the nature of this correlation. The special kind of correlation that is at issue is called an "entangled state." It turns out that entangled states are not just any old correlations, they're quantum mechanical correlations; in fact, as we'll see, quantum entanglements are super-correlations (which outrun any conceivable kind of correlation that can be conjured on the basis of classical physics). But this understanding of quantum entanglements took many decades to develop and much of the research that has yielded significant findings in this regard was conducted after Einstein's death. As far as Einstein and his colleagues were concerned they thought they had the only viable way of explaining the correlated results and this amounted to a return to Newtonian metaphysics. Before we study the details of their argument let's first give the mathematical definition of an entangled state (unraveling its meaning will take much of this chapter).

What is a quantum entanglement? *Entanglements, like superpositions, are uniquely quantum mechanical—they specify a feature of particle behavior for which there is no classical physics equivalent.* In essence, the notion of *an entanglement is a generalization of a superposition to the case of more than one particle.*[28] To illustrate the nature of an entangled state, let's return to the example we considered above of a particle with two possible spin eigenstates—"up" or "down." In order to understand the nature of entanglements we need to consider at least

two such particles, labeled A and B. Since we need to do a bit more bookkeeping for this example, since there are two particles, let's represent an "up" eigenstate for particle A as $(\uparrow)_A$, rather than $(\psi_u)_A$ which uses the same notation as earlier with an additional subscript. An *entangled state* of systems A and B can be symbolized as follows

$$\psi = c_1 (\uparrow)_A (\downarrow)_B + c_2 (\downarrow)_A (\uparrow)_B \qquad (7.7)$$

where c_1 and c_2 are coefficients (i.e., complex numbers). The first term symbolizes that system A's state is $(\uparrow)$ (i.e., when measured, the eigenvalue is "up") and system B's state is $(\downarrow)$ (i.e., when measured, the eigenvalue is "down"). The second term symbolizes the reverse: system A's state is $(\downarrow)$ and system B's state is $(\uparrow)$. There are several important things to notice about this entangled state of A and B. First of all there is a specificity to their entanglement: The equation (7.7) tells us that the states of systems A and B are oppositely correlated—if A's state is up, then B's is down, and vice versa. Crucially, it should be noted that it is *not* possible to write this expression in the form of what is the case for system A times what is the case for system B; that is, ψ cannot be factored into a product of two separate terms (the state of A times the state of B). In other words, the entangled state of systems A and B cannot properly be understood as a composite system, for example, a mixture, composed of two independent components, that is, separately determinate systems A and B. Rather, *the entangled state* of A and B, symbolized by equation (7.7), *must be understood as a single entity*. I will have much more to say about entanglements in what follows. For now, let's return to the EPR argument.

Now that we know some technical details about entanglements, let's examine in greater detail how Einstein, Podolsky, and Rosen propose to circumvent the uncertainty principle. The uncertainty principle for the spin-vector is the following: it is impossible *in principle* to simultaneously determine more than one component of the spin-vector at a time. The EPR experiment is prepared by allowing systems A and B to initially interact and become correlated/entangled. Let's assume for the moment that the EPR entangled state is specified as in equation (7.7).[29] The EPR argument is as follows: if one measures the spin of system A along some axis, let's say the z-direction, and finds "up," meaning the corresponding eigenstate is $(\uparrow)$, then without in any way disturbing system B, that is, by performing measurements *only* on system A, one would know with certainty (i.e., 100% probability) that B's state is $(\downarrow)$ (i.e., this result follows without performing any measurement on B), and vice versa. So now we know one component of

B's spin, the z-component, without having disturbed it. But this does not constitute a violation of the uncertainty principle. To find a way around the uncertainty principle, we would have to determine at least two of its spin components in this way.

It turns out that there is a special state for which the spin components are always oppositely correlated (i.e., if one is "up" the other is "down"), no matter which axis we measure spin along. This is called a singlet state and it is just the state symbolized by equation (7.7) with the following values for the coefficients: $c_1 = \sqrt{\frac{1}{2}}$ and $c_2 = -\sqrt{\frac{1}{2}}$:

$$\psi = \sqrt{\frac{1}{2}}\,(\uparrow)_A(\downarrow)_B - \sqrt{\frac{1}{2}}\,(\downarrow)_A(\uparrow)_B \qquad (7.8)$$

Now we seem to be in a position to circumvent the uncertainty principle: we arrange to have the entangled state be a singlet state and we repeat the method above for determining the spin of B by performing measurements on A, this time in another direction. In fact, no matter which axis we choose we can perform a measurement on system A and know with certainty the spin value of system B along that axis without having disturbed system B in any way. The striking thing about using a singlet entangled state is that whatever the value of the spin of A along some axis turns out to be, the value of B's spin along the same axis will always be oppositely correlated. In other words, the measurement of the spin of system A along any axis *instantaneously* determines the spin of system B along that axis! This is the case even though the systems are presumed to be independent and no longer interacting. Now although it isn't possible to simultaneously measure the spin of system A along two directions simultaneously, such that we know the values of the spin of system B along two directions simultaneously, we can perform a test that amounts to the same thing with regard to the issue at hand if we do the following: since what we are interested in testing is whether or not objects have determinate properties independently of the act of measurement, we can achieve a test of this by arranging for the systems A and B to head away from their source (where they are in an entangled state) in opposite directions, each moving toward a spin detector that can be independently oriented along any of the three directions (x, y, or z) while the particles are on their way there.[30] The key is that the particles can't have "made a prior agreement" to both have definite values of spin in the z-direction, forgoing definite values in the other directions (according to the indeterminacy principle), as they leave the source because it is possible that both SG devices are set in the x-direction, for example, *after* they left the source. And yet, the quantum mechanical prediction is that no matter which axis is chosen for measurement (after the particles have left and are well on their way) the spin values upon measurement will be found to be oppositely correlated! How can this be?

You might argue along with Einstein that while those who believe that quantum mechanics is a complete theory might be hard pressed to *explain* this result, the results can easily be accounted for if we simply agree that physical systems have determinate attributes (all along) independently of their measurement, that is, if we take the classical metaphysical position that the systems each have definite spin values along the three directions. And if quantum mechanics is unable to tell us the values of each of these spin components then the theory is clearly inadequate since any serious theory ought to be able tell us all there is to know about physical reality. This is the essence of the argument made in the EPR paper. Let's look at it a bit more closely.

Einstein and his colleagues reason as follows. The fact that we can determine the value of the spin for system B along any axis without measuring it directly (by taking advantage of the entanglement to perform all measurements on A), that is, without in any way disturbing B means that it must have had these properties all along, because the only other conceivable explanation is that a faster-than-light, indeed instantaneous, form of communication transmits information between A and B, but that of course violates the special theory of relativity. In other words, they claim there are only two possible explanations: (1) the result of a measurement on system A has a nonlocal effect, that is, an instantaneous influence on the physical reality of system B; or (2) quantum mechanics is incomplete. Since they see the first option as being in conflict with the special theory of relativity, they conclude that quantum mechanics must not be a complete theory, and that there must in fact be some other variables, hidden from view, which if discovered would account for all of physical reality, including the values of so-called complementary variables, which they claim to have shown are really simultaneously elements of physical reality after all.

The effect of the EPR paper on Bohr is said to have been "remarkable" (Wheeler and Zurek 1983, 142). Indeed, Bohr's colleague Leon Rosenfeld described the paper as an "onslaught [that] came down upon us as a bolt from the blue" (ibid.). Clearly, a rapid and incisive response was necessary. Bohr dropped everything else and carefully worked and reworked his response, which he had ready in six weeks' time (a record for Bohr, who labored over each paper and wrote multiple drafts up until the time of publication). The essence of his response is contained in the following paragraph:

> From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky, and Rosen contains an ambiguity as regards the meaning of the expression "without in any way disturbing a system." Of course, there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system.* Since these conditions constitute an inherent element of the description of any phenomenon to which the term "physical reality" can be properly attached, we see that the argumentation of the mentioned authors does not justify their conclusion that quantum-mechanical description is essentially incomplete. (Bohr 1935; italics in original)[31]

Bohr challenges the EPR criterion of physical reality. His response emphasizes the fact that the matter of deducing the properties of system B by performing all measurements on system A and thereby not disturbing B in any way whatsoever is a red herring. For Bohr, *disturbance* is emphatically *not* the issue: "Of course, there is in a case like that just considered no question of a mechanical disturbance." More than a simple acknowledgment of the fact that in this case system B hasn't been disturbed (because measurements are performed only on system A), Bohr insists that the very idea that the notion of disturbance is at issue is false.[32] Rather than a question of disturbance, what is at issue for Bohr in our understanding of the nature of physical reality is the objective resolution of the *ontological indeterminacy* between "object" and "agencies of observation": "There is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system"; in other words, the essential issue is the way in which the ontological ambiguity is resolved only for a particular experimental arrangement. If the experimental arrangement is changed, there is a corresponding change in the cut, that is, in the delineation of "object" from "agencies of observation" and the causal structure (and hence "the future behavior of the system") enacted by the cut. Thus Bohr concludes that these "very conditions"—the entire experimental arrangement—which "constitute an inherent element of the description of any phenomena," are necessary to resolve the ambiguity, and consequently "the term 'physical reality' can [only] be properly [that is, unambiguously or objectively] attached" to the notion of a phenomenon that includes the entire experimental arrangement, and not to some abstract notion of an observation-independent object. Bohr rejects the EPR argument on the following grounds: The criterion of physical reality used by Einstein, Podolsky, and Rosen is not objective or unambiguous, since the inherent ambiguity (indeterminacy) of the boundaries and properties of the object that they presume to measure, and presume are determinate from the start, is not resolved outside a given experimental arrangement; and since they use different experimental arrangements to measure different complementary variables, there is an essential ambiguity in their criterion of physical reality.

Did Bohr's response successfully undercut the EPR argument and put the issue to rest once and for all?[33] It is said that Bohr's response satisfied most physicists. Einstein, on the other hand, was not satisfied. Bohr was disheartened that he had not finally convinced Einstein. Whether or not they were ultimately convinced by Bohr's response, most physicists considered the matter settled, if for no other reason than sheer pragmatism: quantum mechanics has proved to be the most successful calculation tool of all time (there's experimental evidence demonstrating that the quantum formalism successfully predicts phenomena in the range from 10^{-10} to 10^{15} atomic radii—25 orders of magnitude), and if the giants of physics couldn't settle the issues concerning the interpretation of the theory, then these philosophical questions would simply be bracketed. It was long assumed that these thought experiments could not be actualized, that there would never be a laboratory face-off between the views of Einstein and Bohr. As far as most physicists were concerned, these issues were "merely philosophical" or metaphysical (literally, beyond the physically testable realm), and there were no physical consequences. And given the positivist ethos of the time, the label "merely philosophical" assumed a pejorative tone and solidified a dismissive stance toward the foundational issue.[34] The foundational issues simply didn't matter.[35]

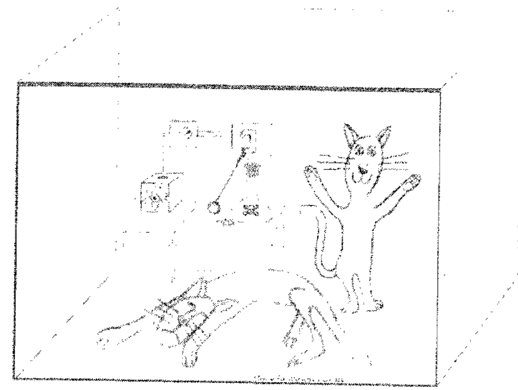
3 SCHRÖDINGER'S CAT PARADOX

Inspired by the EPR paper, Schrödinger made his own offering concerning the problem of measurement in 1935. Although you wouldn't know it from its exceptional notoriety and all that it has come to stand for, the entirety of Schrödinger's discussion of the famous "cat paradox" is limited to a single paragraph of a lengthy exposition on the problem of measurement in quantum theory.[36] The cat paradox is used to dramatize the difficulties of coming to an adequate understanding of the nature of measurement.

Schrödinger introduces the cat paradox in a section preceding his lengthy discussion of measurement, called "Are the Variables Really Blurred?" In this section, he is inviting us to grapple with the notion of the wave function or quantum state of a system. Having already dismissed a statistical or classical ignorance interpretation of quantum probabilities in the previous section of his paper, Schrödinger asserts that the wave function expresses "the degree and kind of blurring of *all* variables in one perfectly *clear* concept" as long as we stick to the microscopic domain. "Blurring" is the metaphor Schrödinger is using to wrestle with the idea of quantum indeterminacy or uncertainty. He notes, however, that concerns arise in taking this metaphor of "blurring" too seriously if one considers what would happen should this "blurring" leak into the world of macroscopic objects:

> At all events [the wave function] is an imagined entity that images the blurring of all variables at every momentum just as clearly and faithfully as the classical model does its sharp numerical values. Its equation of motion [i.e., the SE] too, the law of its time variation, so long as the system is left undisturbed [i.e., no measurement is performed], lags not one iota, in clarity and determinacy, behind the equations of motion of the classical model. So the latter could be straight-forwardly replaced by the ψ-function, *so long as the blurring is confined to atomic scale*, not open to direct control. In fact the function has provided quite intuitive and convenient ideas, for the instance the "cloud of negative electricity" around the nucleus, etc. *But serious misgivings arise if one notices that the uncertainty affects macroscopically tangible and visible things, for which the term "blurring" seems simply wrong*. (Schrödinger 1935; italics mine)

Schrödinger's point is that, between measurements, the Schrödinger equation describes the deterministic time evolution of the wave function—the "blurring," as it were, is propagated forward in time in a deterministic fashion—and it therefore introduces no major conceptual difficulty (seeming much like the familiar classical mechanics with the exception of this "blurriness"). Hence, as long as things are kept on the scale of microscopic objects, blurring proves to be a helpful heuristic.[37] However, when the blurring might have a chance to leak into the world of macroscopic objects, especially during measurements when the microscopic system interacts with a macroscopic measuring instrument, the notion of blurring goes wrong. Schrödinger's point is that despite the blurring of microscopic variables, we don't witness this blurriness upon measurement: the macroscopic variables that we measure have "sharp" values. Schrödinger highlights the absurdity of this notion of blurring on a macroscopic scale by offering the following "quite ridiculous case" (see figure 25):



25 The Schrödinger cat paradox experiment. A cat is placed in a box with a radioactive source. On the table is a Geiger counter with the radioactive source. If the Geiger counter detects a decay event, a relay trips a weight, which hits the flask, which releases the poison, which kills the cat; if no decay is detected, the cat remains alive. The fate of the cat is thereby entangled with the fate of the atom. *Illustration by Mikaela Wilson-Barad for the author.*

> A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, *so* small, that *perhaps* in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives *if* meanwhile no atom has decayed. The first atomic decay would have poisoned it. The ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.
>
> It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be *resolved* by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks. (Schrödinger 1935; italics in original)

There are several important points to make about this passage. Let's concentrate first on the proposed macabre scenario that results in the unfortunate feline being "smeared out in equal parts." What does Schrödinger mean when he speaks of a cat "smeared out" in equal parts? He is referring to a situation in which the system's wave function involves a *superposition* of "alive" and "dead" states of the cat. Let's be clear about what has happened. Notice that this diabolical plot is rigged up in just such a way as to create a situation in which the fate of the cat is *entangled* with some microscopic event, in this case the random decay of an atom (which, in this particular case, has a 50-50 chance of decaying during the period of time we leave the kitty locked up in the chamber with the radioactive source and the poison), so that the superposition in the microscopic world is leaked into the macroscopic world. The question is: How are we to understand superpositions in the macroscopic world? Doesn't the metaphor of blurriness seem obviously inappropriate in this domain? What has happened?

First of all, since there are many misconceptions about the cat paradox, it is important to dispel some incorrect understandings of this "smearing" of the cat (so to speak). It is *not* the case that the cat is either alive or dead and that we simply do not know which; or that the cat is both alive and dead simultaneously (this possibility is logically excluded, since [alive] and [dead] are understood to be mutually exclusive states); or that the cat is partly alive and partly dead (a kitty in a coma); or that the cat is in a state of being neither alive nor dead (a vampire cat living among other "undead" creatures).[38] Rather, the correct way to understand what the "smearing" stands for is to realize that the cat's fate is not simply metaphorically *entangled* with the radioactive source—it is literally in an *entangled state* (in the technical sense discussed earlier). That is, the wave function of the system (that includes both the cat and the atom) looks something like

$$\psi = c_1\,(\text{alive})_{\text{cat}}\,(\text{not decayed})_{\text{atom}} + c_2\,(\text{dead})_{\text{cat}}\,(\text{decayed})_{\text{atom}} \qquad (7.9)$$

where $|c_1|^2$ and $|c_2|^2 = 1/2$; that is, there is a 50–50 chance of either outcome: atom doesn't decay and cat is alive, or atom decays and cat is dead.[39] In other words, the fate of the cat is entangled with the fate of the atom, and in the absence of an appropriate measuring apparatus, their fates are indeterminate. There is a situation for which there is no parallel in classical physics.[40]

Before we get to the crux of the paradox, I want to discuss another important issue raised by Schrödinger's cat in the box. One might wonder if Schrödinger isn't in some sense pulling the wool over our eyes: isn't quantum behavior, like superpositions, for example, limited in principle to the microscopic domain? Despite the popularity of this misconception, this simply does not seem to be the case.[41] No empirical evidence exists to support the assertion that there are two different domains of physical laws: one described by quantum physics and another by classical mechanics. (On the contrary, empirical evidence supports the wider applicability of quantum physics.) Quantum physics supersedes Newtonian physics; it does not merely supplement it. So while the cat paradox is purposefully constructed for its obviously "ludicrous" value, the issue of macroscopic quantum effects cannot be brushed off as one of mere contrivance. Has quantum mechanical behavior ever been observed in the macroscopic domain?

There are three basic reasons why quantum effects are not commonly evident in the realm of our everyday experience. First of all, quantum effects are of the order of the ratio of Planck's constant (h) to the mass of the object in question (m). While electrons, atoms, and other very-small-mass objects have fairly significant h/m ratios, for macroscopic objects, like cats, the ratio of h/m is extremely small. It is not that we live our daily lives in a classical world, rather than a quantum one; the point is that we generally don't notice quantum effects because they are very small (too small to notice without special equipment).[42] Furthermore, quantum behavior is difficult to observe because of the difficulty of shielding an object, especially a relatively large object, from interactions with its "environment," which continually fluctuates in an erratic fashion in such a way that a superposition is "randomized" into a mixture "for all *practical* purposes" (but *not* in principle). This randomization process is called "decoherence." Finally, one has to know how to identify an entanglement (e.g., where to look for correlations and how to measure them), and generally speaking, this is far from evident (see discussion hereafter).

Clearly there are major obstacles to observing quantum behavior for large-scale systems. But however difficult it is to realize in practice, in principle we ought to be able to observe quantum behavior in macroscopic systems. In fact, quantum behavior in relatively large-scale systems such as macroscopic quantum tunneling and macroscopic quantum coherence has been observed. The most well known example is probably Tony Leggett's 1984 experiments on superconducting quantum interference devices, or SQUIDs, for short. So the question of macroscopic quantum states is not an idle matter. Nonetheless this is not what concerns Schrödinger.

The thought experiment offered by Schrödinger is a dramatic staging of an issue that already exists on the microscopic level, which we have in fact already encountered, but doesn't seem quite so disturbing when we talk about microscopic particles. The point is that we are quite confident about what we will find when we open the steel chamber: we won't find a cat "smeared out in equal parts," but rather we will simply find the cat either dead or alive—period. But the point applies as well when we make a measurement on an atom or some other particle: we don't find it in a superposition of eigenstates, but rather in *one* of the possible eigenstates. *The point is that measurement resolves the indeterminacy.* (It is this fact that gives Schrödinger pause in using the term "blurring" to describe reality.) When we observe a system, it ceases to be in a superposition. But how is the indeterminacy resolved? By what mechanism does the system go from a superposition of eigenstates to a definite value measured for the corresponding property? It seems as if the wave function has somehow "collapsed" from a superposition (or entanglement) to one in which all the coefficients except one of them are set to zero, that is, in which only one of the possible eigenstates appears to be selected. But how is such a collapse possible? By what mechanism is the wave function reduced to a single eigenstate?

Crucially, as Schrödinger points out, this so-called collapse of the wave function from a superposition of states to a determinate eigenstate—from indeterminacy to determinacy—is *not* accounted for by the SE. The crux of the matter, then, is how we are to understand the nature of this "resolution," that is, how we are to understand the nature of measurement. This is the central question in Schrödinger's paper, and since it leads us to the heart of the foundations of quantum mechanics, it deserves a section of its own.

4 THE PROBLEM OF MEASUREMENT

The cat paradox captures our imaginations in ways that the same phenomenon involving electrons and neutrons simply doesn't. But the feature that grips us the most—its being part of an entangled state, including a superposition or "smearing out" of dead and alive states—is not what many physicists find most troubling. What is most disturbing, most in need of explanation, is *the nature of the transition of the state during the process of measurement*, not merely the nature of its state beforehand. There is something importantly different about the state of the system before and after measurement. *Upon measurement, the superposition appears to "collapse" into a mixture.*[43] In particular, we don't observe cats in indeterminate states; rather, upon measurement we find the cat either dead or alive. This is no different from the situation that we encounter when we perform measurements on microscopic objects: pointers always point in determinate directions (or at least they seem to). For example, if we use an experimental arrangement suited to measure the spin value in the z-direction, we find some particles with an "up" value and some with a "down" value; and if we perform a two-slit experiment, every particle lands at a determinate position on the screen (even though it doesn't have a trajectory).

The point is that while the SE governs the deterministic linear evolution of the wave function, which indeed allows for the existence of superpositions, entanglements, and other forms of quantum behavior, it seems only to account for what happens to the wave function *between* measurements, and does not seem to describe *the abrupt transition that appears to take place as a result of a measurement*. It is not possible to overemphasize the profundity of this matter for the theory of quantum mechanics: not only does it seem as if the formalism itself is unable to describe what happens during the process of measurement, but the formalism seems unable to give an account of what we even mean by measurement. The significance of this was not lost on Schrödinger, who wrote:

> The abrupt change by measurement . . . is the most interesting point of the entire theory. It is precisely *the* point that demands the break with naive realism. For *this* reason one can *not* put the ψ-function directly in place of the model or of the physical thing. And indeed not because one might never dare impute abrupt unforeseen changes to a physical thing or to a model, but because in the realism point of view observation is a natural process like any other and cannot *per se* bring about an interruption of the orderly flow of natural events. (Schrödinger 1935; italics in original)

Herein Schrödinger begins a thorough analysis of the problem of measurement. It is worthwhile to examine his reasoning at some length:

> The rejection of realism has logical consequences. In general, a variable *has* no definite value before I measure it; then measuring it does *not* mean ascertaining the value that it *has*. But then what does it mean? There must still be some criterion as to whether a measurement is true or false, a method is good or bad, accurate, or inaccurate—whether it deserves the name of measurement process at all. Any old playing around with an indicating instrument in the vicinity of another body, whereby at any old time one then takes a reading, can hardly be called a measurement of this body. Now it is fairly clear: if reality does not determine the measured value, then at least the measured value must determine reality—it must actually be present *after* the measurement in *that* sense which alone will be recognized again. That is, the desired criterion can be merely this: repetition of the measurement must give the same result. By many repetitions I can prove the accuracy of the procedure and show that I am not just playing. (Schrödinger 1935; italics in original)

(Things are beginning to sound rather Bohrian.) Schrödinger finds that it is necessary to dig down to the very foundation of the theory: If measurements do not reveal preexisting values but rather in some sense create the values, then how can we be sure we are not merely playing around, but rather learning something about nature? Can we provide any objective basis for experimental results? What is the nature and role of measurement? Does quantum mechanics give us any handle on the nature of measurement? If quantum physics cannot account for measurement processes, what then?

Clearly the stakes are high here. We have in quantum mechanics a formalism built on the ability to predict the results of observations, and yet the formalism does not seem to provide an understanding of the very nature of measurement—itself a physical process that should obey the laws of quantum physics. Schrödinger takes the following line of reasoning as a clue. He points out that as the wave function changes—either continuously, if left on its own, or discontinuously, as a result of a measurement—the "expectation-catalog of predictions" changes, which means that "in the catalog not just new entries, but also deletions, must be made. No knowledge can well be *gained*, but not *lost*. So the deletions mean that the previously correct statements have now become incorrect. A correct statement can become incorrect only if the *object* to which it applies changes" (Schrödinger 1935; italics in original). He then invokes the fact that measurement interactions are also "natural process[es] like any other" to place the burden where he believes it belongs, not in some allegedly new law of nature governing measurement processes (as opposed to the law that governs the continuous evolution of the wave function between measurements), but in our understanding of the nature of the wave function itself: "Since [measurement] does interrupt that of the ψ-function, the latter . . . can *not* serve, like the classical model, as an experimentally verifiable representation of objective reality." Schrödinger sums up thus:

> 1.) The discontinuity of the [wave function] due to measurement is *unavoidable*, for if measurement is to retain any meaning at all then the *measured value*, from a good measurement, *must* obtain. 2.) The discontinuous change is certainly not governed by the otherwise valid causal law [that is, the SE], since it depends on the measured value, which is not predetermined. 3.) The change also definitely includes (because of "maximality") some *loss* of knowledge, but knowledge cannot be lost, and so the object *must* change—*both* along with the discontinuous changes and *also*, during these changes, in an unforeseen, *different* way. (Schrödinger 1935; italics in original)

This is the point at which Schrödinger introduces the notion of an entangled state:

> This is the point. . . . *Maximal knowledge of a total system does not necessarily include total knowledge of all its parts, not even when these are fully separated from each other and at the moment are not influencing each other at all.* . . . Any "entanglement of predictions" that takes place can obviously only go back to the fact that the two bodies at some earlier time formed in a true sense *one* system, that is were interacting, and have left behind *traces* on each other. . . . When two systems interact, their ψ-functions . . . do not come into interaction but rather they immediately cease to exist and a single one, for the combined system takes their place. . . . As soon as the systems begin to influence each other, the combined function ceases to be a product and moreover does not again divide up, after they have separated, into factors that can be assigned individually to the systems. Thus one disposes provisionally (until the entanglement is resolved by an actual observation) of only a common description of the two. (Schrödinger 1935; italics in original)

Clearly Schrödinger is alluding to the kind of situation that interests Einstein, Podolsky, and Rosen. Schrödinger then goes on to argue, perhaps surprisingly, that the entanglement is "resolved" not at the point when the trace is registered (when marks are made on bodies) but when a "living subject actually take[s] cognizance of the result of the measurement." In other words, going back to the example of the cat, the scenario of resolution that Schrödinger suggests leads us to the following bizarre situation. Suppose that we attach a device to the exterior of the chamber, which after one hour automatically opens the box and records the result of what has happened inside. Now, one would presume that after one hour, the atom has already decayed or not, and consequently the cat is already dead or not, and the recording device has thus made a record of the fact of the matter. But according to Schrödinger, this presumption would be incorrect. Rather than a resolution of the entanglement, what we have is a situation of *further entanglement* in which the recording device is now in an entangled state as well, entangled with everything going on inside the chamber. Indeed, Schrödinger argues that the entanglement persists until some cognizing subject has a look at the trace left on the recording device, which upon inspection now assumes a definite value. Schrödinger warns that this should not be understood as the result of some kind of mental agency (e.g., a kind of telekinesis):

> *Not until this inspection*, which determines the disjunction, does anything discontinuous, or leaping, take place. One is inclined to call this a *mental* action, for [things can be set up such that the] object is already out of touch [by the time this inspection takes place], is no longer physically affected: what befalls it is already past. But it would not be quite right to say that the ψ-function of the object which changes *otherwise* according to a partial differential equation, independent of the observer, should *now* change leap-fashion because of a mental act. For it had disappeared, it was no more. Whatever is not, no more can it change. It is born anew, is reconstituted, is separated out from the entangled knowledge that one has, through an act of perception, which as a matter of fact is not a physical effect on the measured object. (Schrödinger 1935; italics in original)

Thus for Schrödinger the problem of measurement is resolved as follows: what appears to be a discontinuous change in the wave function is not due to some distinctive law of nature governing measurement interactions that creates a discontinuous change in the wave function; but rather what is actually going on is that the wave function of the "object" becomes entangled with the "measuring system" (and such an entanglement is governed by the SE) such that they are no longer separate systems. Only upon observation by *a cognizing agent* can we speak of a resolution of the entanglement. In other words, there is no question of an abrupt physical change that corresponds to this change in the wave function; rather, the shift in the wave function of the object is due to the entanglement of our *knowledge* of the "object" with our *knowledge* of the "measuring instrument" in just such a way that although we still have maximal knowledge of the overall wave function, we no longer have knowledge of the individual subsystems (they aren't even well-defined). In other words, Schrödinger, who explicitly warns against a naive realist interpretation of the wave function, resolves the problem of measurement on the basis of his understanding of the wave function as a catalog of the maximum knowledge of a system that it is possible to obtain in principle. Hence Schrödinger's understanding of the notion of entanglement is *explicitly epistemic*, not ontic.[44] In the defining sentence, in fact, he explicitly speaks of the "*entanglement* of our knowledge" (161).

I have taken us through the Schrödinger paper in some detail, rather than doing an allegedly pedagogically motivated "cut to the chase," for several reasons. First of all, it is remarkable how this single paper authored in 1935 brings to the fore so many of the issues concerning the problem of measurement that have continued to circulate more than a half century later. Especially important is the relationship between the problem of measurement and understanding the nature of the wave function. Second, unlike many contemporary encapsulations of the issues, a detailed examination shows just how serious the problem of measurement is. Third, it shows what is at issue and at stake for Schrödinger in his introduction of the notion of an entangled state, and just what he means by it. This latter point is especially important for my purposes because some scholars have wondered what the relationship is between Schrödinger's entanglement of states and Bohr's notion of a phenomenon.[45] I will return to this issue later in the chapter.

The notion of the collapse of the wave function surfaces in nearly every discussion of what has become known as "the measurement problem," and yet there is no mention of a "collapse" in Schrödinger's paper. As we have seen, the key issue is how to understand the abrupt change in state between the superposition or entanglement that precedes the measurement and its "resolution" into a mixture of definite values upon measurement. Recall that the two kinds of states are physically distinguishable: superpositions leave interference traces, and mixtures do not. When this change of state is taken literally, that is, as something physical (which it is most often assumed to be), it is referred to as a "collapse" of the wave function. The reason there is no mention of a "collapse" in Schrödinger's paper should then be obvious: Schrödinger does not understand the abrupt change in the wave function as corresponding to a physical change. The reader who has been exposed to modern accounts of the problem of measurement or of the Schrödinger cat paradox may in fact be startled to find that the collapse of the wave function is *not* a necessary way to understand what happens upon measurement. But faced with this single option, the question of the nature of measurement really does turn into the "measurement problem," because the collapse is truly extraordinary in that "*the collapse must take place instantaneously over all space*" (Greenstein and Zajonc 1997, 183; italics in original); but now we are really in trouble because the formalism (meaning the SE) cannot account for the collapse:

> We conclude that the collapse of the wave function occupies an anomalous position within quantum mechanics. It is *required* by the fact that observations occur, but it is not predicted by quantum theory. It is an additional postulate, which *must* be made in order that quantum mechanics be consistent. (Greenstein and Zajonc 1997, 187; italics mine)[46]

This additional postulate is called the "projection postulate," and it is an ad hoc addendum to the theory introduced by the mathematician John von Neumann. However, collapse is *not* the only option:

> We must also mention the view, held by certain workers in the field, that the wave function has no physical meaning at all. Rather they hold that the wave function should be understood as describing *our information about a system*. In this view, the collapse of the wave function has no particular significance. . . . On the other hand, we should note that most physicists regard a change in the wave function as corresponding to a physical process, as opposed to a change in our knowledge of that process. (Greenstein and Zajonc 1997, 188; italics in original)

But this is not the case for Schrödinger. And more to the point, science teaches us that we should be skeptical about any argument based on what the majority does or does not believe. Indeed, one must be particularly vigilant in this regard when it comes to foundational issues in quantum mechanics.

With this important caveat, we return to the question of the alleged collapse. In what sense, if any, does the projection postulate account for the "collapse"? In essence, the projection postulate is nothing more than a mathematical restatement of the alleged collapse of the wave function; that is, it is a formal statement to the effect that upon measurement we get a definite value for the property measured (that is, the measuring instrument's "pointer" points in the direction of *one* out of all the possible eigenvalues). Many physicists and philosophers of physics endorse the projection postulate and take it to be a well-established feature of the so-called Copenhagen interpretation. However, although the nature of measurement is central to Bohr's analysis, Bohr never mentions the projection postulate, and there is no evidence that he advocates including it as a fundamental element of the Copenhagen interpretation. It does not seem to play any role whatsoever in understanding quantum physics.[47] (As I argue later, I believe there is a good reason for this: as far as Bohr is concerned there is no need for the projection postulate.) Even those who endorse the projection postulate acknowledge the dissatisfaction in its completely ad hoc nature. First of all, there is the fact that the projection postulate clearly does not correspond to a real physical process (not if the theory is to remain in its original form as proposed by Schrödinger, that is, not if the SE is considered to describe a natural law).[48] Furthermore, to make matters worse, the postulate is only sometime required. (In the case where the initial state of the object corresponds to one of the eigenstates of the measuring instrument, no projection postulate is required, that is, the SE itself predicts the measured result, as we have seen.)[49]

Although the majority of physicists claim allegiance to the Copenhagen interpretation of quantum mechanics, the fact is that there is no single determinate sense of *the* Copenhagen interpretation, but rather a pastiche of views that is referred to under this umbrella term.[50] Dissatisfaction with the so-called Copenhagen interpretation of quantum mechanics, particularly with regard to its proposed resolution of the measurement problem, has prompted many creative alternatives, including the collapse of the wave function by consciousness (Wigner 1961) or by gravity (Penrose 1989); the theory that the wave function never collapses, but instead upon measurement the world is split into many worlds such that each possibility is actualized (Everett 1957);[51] Bohm's (1952) nonlocal hidden-variables theory, which restores determinism, at the expense of other prized classical ideals, and has no need for a collapse; the GRW formalism (Ghirardi et al. 1986), which suggests an alternative to the SE that includes a term that causes a physical collapse of the wave function; decoherence, which provides a physical mechanism for collapse on the basis of the interaction of the object with a randomly fluctuating environment; the transactional interpretation (Cramer 1986), whereby the collapse takes place when the "confirmation wave" is emitted following the "offer wave," which is based on the preparation procedure of the experiment; the participatory universe interpretation (Wheeler and Zurek 1983); the quantum logic interpretation; the modal interpretation; and others. In her essay "Cognitive Repression in Contemporary Physics," Evelyn Fox Keller attributes "the failure of physicists to formulate a cognitive paradigm adequate to their theory" to an unwillingness to let go of the basic tenets of classical physics: the objectivity and knowability of nature. "What is required instead," she suggests, "is a paradigm that on the one hand acknowledges the inevitable interaction between knower and known, and on the other hand respects the equally inevitable gap between theory and phenomena" (Keller 1985, chap. 7).[52] Referring to Keller's cognitive repression diagnosis, Anton Zeilinger (1996) proffers his own diagnosis of the psychosocial factors that have led to this proliferation of alternative interpretations or theories: "The search for interpretations different from the Copenhagen interpretation very often is motivated by trying to evade its radical consequences, that is, an act of cognitive repression on the part of the proposers."

EXPERIMENTAL METAPHYSICS: THE REALIZATION OF GEDANKEN EXPERIMENTS IN THE LAB

> *Gedanken* (/g*-dahn'kn/adj.) 'Gedanken' is a German word for 'thought.' A thought experiment is one you carry out in your head. In physics, the term 'gedanken experiment' is used to refer to an experiment that is impractical to carry out, but useful to consider because it can be reasoned about theoretically.
>
> —*The Jargon Dictionary*

> Gedanken experiment: An experiment carried out only in imagination or thought; an appeal to imagined experience; a *thought experiment.*
>
> —*Oxford English Dictionary*

For decades, Einstein and Bohr were locked in a passionate debate concerning the correct interpretation of the quantum formalism. They made famous use of gedanken experiments to challenge each other's understanding of quantum phenomena. Gedanken, or thought, experiments are imagined experiments used to focus on the crucial aspects of a particular problem. There is no expectation that a gedanken experiment will ever be performed (on the contrary), and therefore there are no practical restrictions. The experiment is only performed in theory—or at least this is true in theory.

One of the fascinating aspects of the gedanken experiments that Bohr and Einstein considered is that they test the realm of the "metaphysical"—that which lies beyond the physical domain. Questions about the nature of reality and of knowledge—such as "If no one measures a property of an object, does it exist?"—are fair game in the imaginary laboratory of the mind. One does not rely on empirical evidence to adjudicate competing claims. Superior argumentation wins the day.

But recently something startling has happened. Experimental, technological, and theoretical progress has made it possible to *actually perform* certain *thought* experiments, experiments that directly test the *metaphysical* foundations of the quantum theory. Welcome to the world of "experimental metaphysics"! It is now possible to perform experimental tests of whether physical reality can in fact be described by a local hidden-variables theory (i.e., a local theory that assumes that objects possess discrete attributes), whether the determination of "which-path" information destroys the interference pattern, whether measurement disturbs a preexisting property or produces a determinate value from a previous indeterminate one, whether there is a viable ontological interpretation of entanglements that explains the nature of measurements, and various other amazing explorations of quantum phenomena. Some of these remarkable experiments are covered in the following subsections:[53]

1 The EPR Challenge and Bell's Inequalities
2 Complementarity I: BKS and Contextuality
3 Complementarity II: Which-Path Experiments (indeterminacy, not uncertainty)
4 Complementarity III: Quantum Erasers—Entanglements Rule!

Unfortunately neither Einstein nor Bohr lived to see these experimental realizations of these crucial gedanken experiments. We are left to our own imaginings as to what their responses might have been.

1 THE EPR CHALLENGE AND BELL'S INEQUALITIES

> [The] metaphysical implications are profound. The experimental tests of Bell's inequalities . . . go so far as to change the very way we should think of physical existence at its most fundamental level.
>
> —GEORGE GREENSTEIN AND ARTHUR G. ZAJONC, *The Quantum Challenge*

With a six-page paper published in 1964, John Bell reconfigured the disciplinary boundaries between philosophy and physics. He showed that it is possible to *empirically* differentiate between two different *metaphysical* positions! It is important to pause for a moment and breathe in the implications of Bell's elegant little paper. It's not as if the boundary between the physical and the metaphysical has remained rigidly fixed through all time, or even for the half century directly preceding Bell's remarkable result; but what we are talking about here is nothing less than the possibility of empirical answers to age-old metaphysical questions such as whether objects possess determinate properties independently of our measurement of them, or, as Einstein quipped, "Is the moon really there when no one is looking?"[54]

The specifics: Bell showed that there is a physically testable difference between the kind of "hidden variables" theory that Einstein, Podolsky, and Rosen argued for in their 1935 paper and quantum mechanics. In particular, using Bohm's mathematically less complex and conceptually more straightforward example (of two systems with entangled spin degrees of freedom that we used in the earlier discussion of the EPR paradox), Bell mathematically formalized the argument of Einstein, Podolsky, and Rosen and derived an inequality that holds for *any* local hidden-variables theory and is violated by quantum mechanics. Therefore Bell made it possible to do an experimental test that tells us whether physical reality is correctly described by a local hidden-variables theory or by quantum mechanics.

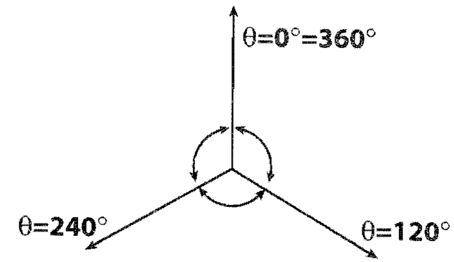
The basic idea is as follows. An entangled state of two systems (e.g., two two-state systems, like two spin-1/2 particles), call them systems A and B, is produced by a source that emits the component systems, A and B, in opposite directions. We place detectors, spin-measuring devices, equidistant from the source so that the spin values of A and B are measured simultaneously. The directions of the spin axes of the detectors (i.e., the magnetic fields of each of the spin-measuring devices) are set independently from each other (so that they may or may not be the same for a given run). The experimenters who set the directions of the detectors for each run of the experiment and record the value of the spin measured are almost universally called Alice (who monitors system A) and Bob (who monitors system B).[55] Now suppose the source emits the two systems in a singlet entangled state described by

$$\psi = \sqrt{\frac{1}{2}}\,(\uparrow)_A(\downarrow)_B - \sqrt{\frac{1}{2}}\,(\downarrow)_A(\uparrow)_B \qquad (7.10)$$

This expression represents the fact that there is a 50–50 chance of getting either correlated set of spin values (A "up" and B "down" or A "down" and B "up") when experimenters set their measuring devices along the same direction (e.g., the z-direction). Clearly, then, if Alice and Bob both set their spin-measuring devices to measure spin in the same direction, they will get opposite results: if one measures "up," the other necessarily measures "down." (In fact, this [anti]correlation result for spin measurements for A and B along the same axis can serve as a useful test to make sure the equipment is working correctly.) For each run, Alice and Bob are free to choose any of three directions. For the sake of this experiment, the three spin axes are oriented in the same plane at a 120° from each other (figure 26).

An individual run, then, consists of the source emitting a pair of correlated particles that travel toward the detectors that Alice and Bob monitor. After the source emits the particles, Alice and Bob randomly choose one of the three directions ($\vartheta = 0°$, 120°, or 240°) for their spin-measuring devices. Then each records the result for his or her detector (+1 for "up," −1 for "down"), as well as the angle specifying the direction of the measuring device (Alice's detector is set at angle ϑ_A; Bob's detector is set at ϑ_B). For a single run, the net result is just the value that A obtained times the value that B obtained. For example, in the case where Alice and Bob orient their devices along the same axis, this product is necessarily −1, since the spins are necessarily oppositely correlated: $(1)(-1) = (-1)(1) = -1$. When all the runs are complete, we calculate some averages. Let $E(\vartheta_A, \vartheta_B)$ stand for the expectation value, or the average value over all runs, of the products of A's spin values times B's spin values when A's detector is oriented at ϑ_A and B's detector is oriented at ϑ_B. Bell showed that for any local hidden-variable theory—the kind advocated by Einstein, Podolsky, and Rosen—the following inequality must be obeyed:

$$|E(\alpha, \beta) - E(\alpha,\gamma)| < 1 + E(\beta,\gamma)$$



26 This diagram shows the orientation of the three possible spin axes, separated from one another by 120°. *Illustration by Nicolle Rager Fuller for the author.*

where $E(\alpha,\beta)$ means that the result with the angle of Alice's device set at $\vartheta_A = \alpha$, and the angle of Bob's device set at $\vartheta_B = \beta$, and similarly for $E(\vartheta, \gamma)$ and $E(\beta, \gamma)$. On the other hand, it is a straightforward calculation in quantum mechanics to show that this inequality is in fact violated.[56] A remarkable feature of this result is that this inequality must hold not merely for *a particular* local hidden-variables (or, more precisely, a local determinate-properties) theory but for *any* such theory.[57] Therefore all we have to do is run this experiment and test out this inequality: if it is obeyed, Einstein, Podolsky, and Rosen are right, but if it is violated, they cannot be right. Indeed, Bell's inequality says that any local hidden-variables theory must obey this inequality, and therefore if it is not obeyed, then reality is not correctly described by a local hidden-variables theory.

Considering the profundity of Bell's theorem, it is an interesting sociological fact that for many years after its publication scant attention was paid to this result (Ballantine 1987). It is difficult not to read this as a measure of the lack of interest in foundational issues in quantum theory in a resolutely neopositivist period. But a small number of philosophically minded theorists went to work clarifying the assumptions on which the inequality is based, and a small number of experimentalists began conducting tests of Bell's inequality.[58]

The result? Not only do experimental tests of Bell's inequality overwhelmingly confirm a violation of the inequality, but the degree of violation is just what is predicted by the quantum theory. That is, *the experimental tests indicate that the EPR analysis is wrong*. Despite the brilliant argument of Einstein and his colleagues, nature is not correctly described by a local hidden-variables theory (along the lines suggested by classical physics). Rather, *there is empiri-*

cal evidence for the existence of a different metaphysics than the one underlying Newtonian mechanics (one famous example of a local determinate-property theory). This is no mere philosophical prejudice but an empirical fact—and this point in itself is already a stunning result.

What are the particular implications of this result for thinking about the nature of reality? To get a handle on this, let's take a closer look at the assumptions that Einstein, Podolsky, and Rosen used and Bell incorporated in his formulaic representation. According to Bell (1964), there are two primary assumptions involved: (1) the so-called reality condition, sometimes also called the "hidden variables condition," but perhaps should more appropriately be called the "inherent properties condition" (individual objects have determinate properties); and (2) the locality condition (nothing done at one location can have instantaneous causal effects at another location). The fact that Bell's inequality is found to be violated empirically means that one, or both, of these assumptions are incorrect.[59] The metaphysical implications are profound:

> The experimental tests of Bell's inequalities . . . go so far as to change the very way we should think of physical existence at its most fundamental level. No longer is it possible to think of the microworld in the terms Einstein, Podolsky, and Rosen advocated. Rather we must think in terms of nonlocality, and/or we must renounce the very idea that individual objects possess discrete attributes. But since Galileo's description of primary quantities, all of science has held to the idea of definite attributes for individual objects. (Greenstein and Zajonc 1997, 144)

Hence the result of the experimental realization of Bell's conception of the EPR gedanken experiment is that it is no longer possible to embrace the metaphysics of individualism (as in classical physics): *either the very idea that individual objects possess discrete attributes is wrong, or interactions among objects are nonlocal, or both.*

2 COMPLEMENTARITY I: BKS AND CONTEXTUALITY

> The "context" of the measurement . . . is an important consideration for quantum systems. . . . this is even true when all the observables are compatible! . . . this [result] is not due to Heisenberg's uncertainty principle, but is an independent feature of quantum theory that has come to be called contextuality.
>
> —GEORGE GREENSTEIN AND ARTHUR G. ZAJONC, *The Quantum Challenge*

> The essential lesson of the analysis of measurements in quantum theory is thus the emphasis on the necessity, in the account of phenomena, of taking the whole experimental arrangement into consideration.
>
> —BOHR, *The Philosophical Writings of Niels Bohr*

In this section I discuss a less well-known, but no less profound, theorem by Bell (1966), further refined by Kochen and Specker (1967).[60] The BKS theorem, as it has become known, is an important theoretical result that provides further insight into the theory of quantum mechanics. It does not require experimental confirmation per se and so perhaps doesn't properly belong in a section called "Thought Experiments Realized." However, I include it here because it makes an interesting bridge between the preceding subsection and the remaining ones and has important implications for understanding the experimental results.

Recall that the indeterminacy principle specifies a limit on the simultaneous measurement of complementary variables. As a result, the quantum state of a system is specified not by all the variables that classical mechanics requires in its specification of state (e.g., the position and momentum of each object at a given time), but by only those variables that are mutually compatible (i.e., are simultaneously determinable). Students of quantum mechanics are taught to find a "complete set of compatible ('commuting') variables" for the system in question. It may come as a shock, then, to these students (and some physicists) to find that interpretational issues present themselves even when dealing with *compatible* variables. More specifically, the BKS theorem shows that according to quantum mechanics, the "context" of a measurement matters even when all the observables are compatible. That is, the value of a particular variable depends on how an experiment may be set up to measure other variables, even when there is no incompatibility (mutual exclusivity) at issue. Significantly, then, the BKS theorem is independent of the indeterminacy relations. This result seems unintuitive not only from the perspective of classical physics but even to many trained in quantum physics. "To put it dramatically, the hair color you detect may well depend on whether you are simultaneously measuring shoe size and gender, or whether you are measuring height and weight" (Greenstein and Zajonc 1997, 115–16).

The BKS theorem, like Bell's inequality, places a limit on the possibilities for viable theories of quantum phenomena. According to the BKS theorem, local hidden variables theories that presume that objects have inherent properties do not agree with the results of quantum theory.[61] Greenstein and Zajonc nicely sum up the implications of the BKS theorem:

> Quantum mechanics is completely in agreement with the BKS theorem because quantum theory in no sense presupposes that the values that observables take on were pre-existing. In choosing one triad [of directions] to measure, the experimenter must configure her apparatus in a particular way and not some other. Changing her choice of which three directions to measure requires a new experimental arrangement. Bohr insisted that one not "imagine" a pre-existing real world whose observables already possess real values: rather *one should ask a theory to make statements only about those variables for which the apparatus is currently configured*. Thus, on his view, we should discuss only one triad at a time. If one resists Bohr's stance, BKS [nonetheless] places profound constraints on the kind of theory and interpretation we can consider. *It must be contextual*. (1997, 116; italics mine)

According to the BKS theorem, every viable theory and interpretation of quantum phenomena must be "contextual."[62] The point is that *the larger experimental arrangement matters for all measurements* (even the measurement of compatible variables). This is a point that Bohr repeatedly emphasized. Significantly, *the BKS theorem rejects the metaphysics of individualism—the assumption that preexisting objects (individually determinately bounded entities) possess inherent properties*.

3 COMPLEMENTARITY II: WHICH-PATH EXPERIMENTS

> The two-slit experiment "has in it the heart of quantum mechanics. In reality, it contains the *only* mystery."
>
> —FEYNMAN ET AL., *The Feynman Lectures on Physics*

In this section I examine the experimental evidence that holds the possibility for adjudicating between the competing accounts of the reciprocal nature of the relationship between complementary notions such as "wave" and "particle" or "position" and "momentum." On the one hand, the explanation that Heisenberg offers is based on the notion that measurements entail disturbances that pose a limit to what we can know. By contrast, Bohr argues that what is at issue is the limits of the simultaneous determinability of complementary variables as a result of the fact that they require mutually exclusive experimental conditions for their determination. For Bohr, there is no question of a disturbance being at issue, since the corresponding properties are not determinate in the absence of an intra-action with a specific measuring instrument, and hence there are no preexisting values to disturb. In Bohr's account, this reciprocal limit relation is not to be given an epistemic interpretation but rather to be understood in terms of the limits of semantic and

ontic determinacy. Before we consider the actual tests, it is worth considering the differences between their perspectives in more detail.

3a. Complementarity and uncertainty

Is the electron a wave or a particle? Even after the achievement of a quantum formalism for physics in 1926, the specter of wave-particle duality continued to haunt physicists:

> In spite of having a mathematical scheme both from Schrödinger's side and from the matrix side, and in spite of seeing that these mathematical schemes are equivalent and consistent and so on, nobody could know an answer to the question: "Is an electron now a wave or is it a particle, and how does it behave if I do this and that and so on." [These] paradoxes became so much more pronounced in that time. . . . The paradoxes by no means disappeared, but on the contrary got worse and worse because they turn out more clearly. . . . Bohr would say "even the mathematical scheme does not help. I first want to understand how nature actually avoids contradictions." . . . To this fundamental problem it looked as if the new mathematical tool[s] did give no clear answer yet. One just had no clear way of really talking about it. That was the stage in the autumn of '26.[63]

Heisenberg and Bohr worked intensely on this problem from the autumn of 1926 into the early months of 1927. Tensions developed between them, and in February Bohr decided to go skiing in Norway to collect his thoughts. Shortly thereafter Heisenberg retreated to Helgoland to escape a bout of hay fever.[64] Both Bohr and Heisenberg found the break in their intense discussions to be very productive. While on vacation Bohr developed his complementarity framework (which he explicitly offered as an alternative to the framework provided by classical physics), and Heisenberg came up with the uncertainty principle that goes by his name. It is said that these two ideas form the backbone of the Copenhagen interpretation of quantum mechanics. I discuss both ideas in chapter 3. There I also note Bohr's disagreement with Heisenberg's interpretation of the mathematical expression that is known as the uncertainty principle and propose that Bohr's alternative interpretation be understood as a principle in its own right, which I label the "indeterminacy principle." The uncertainty principle and the indeterminacy principle are competing claims about how we should understand the relations of reciprocity (including the well-known expression $\Delta x \, \Delta p \geq \hbar/2$) which may be derived mathematically from the formalism of quantum mechanics.[65] In this chapter, I examine some new experiments that have only very recently been performed that promise to determine which of these competing claims is best supported by the evidence. The first step is to see if we can sort out the relationship between complementarity and what I have dubbed the indeterminacy principle, and to clearly explicate the differences between the "uncertainty principle" and the "indeterminacy principle" and their significance.

A vitally important and yet completely unappreciated fact is that Bohr actually derived a quantitative relationship of complementarity in his 1927 Como lecture (or at least one particular form of it). Before I reveal this relationship, let's examine Bohr's derivation in some detail. This derivation also has the virtue of emphasizing several important points that will be pertinent to our understanding of the experimental results.

Bohr begins by explaining that theoretical concepts—like position, momentum, space, time, energy, causality, observation, and particle and wave—that classical physics takes for granted need to be properly understood as idealizations or abstractions; in the absence of appropriate experimental arrangements, concepts do not have determinate meanings. For example, in the following passage, Bohr emphasizes that the classical notions of "wave" (i.e., "radiation in free space") and "particle" (i.e., "isolated material particles") are but abstractions, and that the notions of "wave" and "particle" are only "definable and observable through their interactions with other systems." He also refers to complementarity as a quantum alternative to the classical mode of description and as a means of reconciling the seemingly contradictory results (i.e., wave and particle behaviors) that electrons, to take one example, exhibit under complementary circumstances:

> Here again we are not dealing with contradictory but with complementary pictures of phenomena, which only together offer a natural generalization of the classical mode of description. In the discussion of these questions, it must be kept in mind that, according to the view taken above, radiation in free space as well as isolated material particles are abstractions, *their properties on the quantum theory being definable and observable only through their interaction with other systems*. (Bohr 1963a [1927 essay], 56–57; italics mine)

We may think we know what "particle" and "wave" mean through the habits of classical physics, but in the usual abstract sense these terms are only idealizations; objectively speaking, unambiguous meanings for these concepts derive from specific material arrangements, and since mutually exclusive experimental arrangements are required to define "particle" and "wave" behaviors, the theory is saved from potentially fatal inconsistencies.[66]

The next section of Bohr's paper was unfortunately given the bland, understated title "Quantum of Action and Kinematics," when what was called for was some eye-catching title that would set this section off in a way that signaled its importance, something like "The Complementarity Relations" or "The Indeterminacy Relations." Indeed, Bohr makes the following important remark just preceding this section:

> An important contribution to the problem of a consistent application of these methods has been made lately by Heisenberg. In particular, he has stressed the peculiar reciprocal uncertainty which affects all measurements of atomic quantities. Before we enter upon his results, it will be advantageous to show how the complementary nature of the description appearing in this [reciprocity relation] is *unavoidable already in an analysis of the most elementary concepts employed in interpreting experience*. (57; italics mine)

In other words, Bohr is about to show that the complementary nature of descriptive terms that show up in the uncertainty relations of Heisenberg can already be accounted for by an analysis of the use of descriptive terms that reveals their reciprocal definability. That is, no consideration of any alleged disturbance is required; all that is needed is a thoroughgoing analysis of the use of physical concepts employed in interpreting the results of measurements.

Bohr starts out this section by remarking on the fundamental "contrast" (i.e., reciprocity) between wave and particle characteristics as expressed in the wave-particle duality (de Broglie–Einstein) relations:

> If Planck's constant be denoted by h, as is well known,
>
> $$E\tau = p\lambda = h, \qquad (1)$$
>
> where E and p are energy and momentum respectively, τ and λ the corresponding period of vibration and wavelength. In these formulae *the two notions of light and also of matter enter in sharp contrast*. While energy and momentum are associated with the concept of particles, and, hence may be characterized according to the classical point of view by definite space-time co-ordinates, the period of vibration and wave-length refer to a plane of harmonic wave train of unlimited extent in space and time. *Only with the aid of the superposition principle does it become possible to attain a connection with the ordinary mode of description*. (57–58; italics mine)[67]

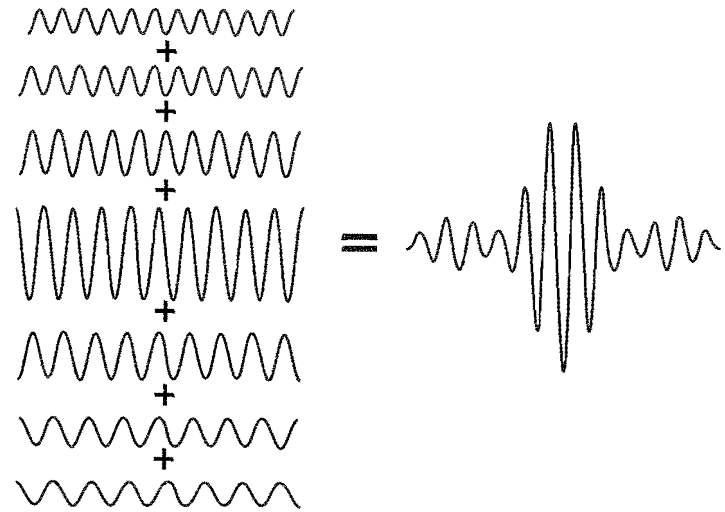
According to Bohr, what is needed to draw a connection between the idealized notions of "wave" and "particle" and the ordinary mode of description (which, according to Bohr, is required when one attempts to make contact with empirical results) is their objective (i.e., unambiguous) empirical realization, which depends on the superposition principle.[68] Why the superposition position principle? Using the superposition principle, it is possible to combine (superpose) component waves, each of well-defined wavelength, to form a wave packet localized in space. (Particles are objects that are localized in space, whereas waves are disturbances that are spread out in space.) Figure 27 shows how one can build a wave packet that is localized in space (shown on the right), of finite spatial extent Δx, by superposing (i.e., adding up) a number of different component waves (in this case the seven different waveforms shown to the left), each with a different definite wavelength.

The key point of Bohr's analysis is to show that there is a necessary reciprocal relationship between the finite spatial extent of the wave packet Δx (its localizability and ultimately its definability as a "particle") and the finite spread of wavelengths $\Delta\lambda$ (its definability as a "wave"). That is, the definability of "wave" ("wavelength") and the definability of "particle" (or "localizability," i.e., "position") stand in a reciprocal relation. In fact, Bohr explains that it is straightforward to derive a quantitative relation between the two,

$$\Delta x \, \Delta k \geq 1/2 \qquad (1)$$

where k, the "wave number" (or reciprocal wavelength), is defined as $2\pi/\lambda$.[69]

It is instructive to consider two limiting cases of this reciprocity relation: (i) $\Delta x = 0$, $\Delta k \to \infty$; and (ii) $\Delta x \to \infty$, $\Delta k = 0$. The first case corresponds to an infinitely narrow wave packet with a perfectly well-defined position (in which case the notion of wave number or wavelength is completely meaningless). Classically, this is how we think of a particle (i.e., it is completely localized in space and has no well-defined wave characteristics). Conversely, the second case corresponds to an elementary monochromatic (i.e., single wavelength) wave with a completely well-defined wave number but no meaningful notion of "position," since it is spread out evenly across all of space. Classically, of course, this is how we think of a wave. The actual wave packet shown in figure 27 is an intermediate case, wherein the wave characteristics are definable within Δk, and the particle characteristics are definable within Δx. That is, one can meaningfully speak of "wave" and "particle" characteristics, but only within their respective limits, and these limits are inversely related to one another. From here Bohr only needs one small step to derive a quantitative expression of complementarity.



27 Illustration showing how to make a wave packet from component waves. The left-hand side of the diagram shows individual monochromatic waves—each one has a given wavelength (a set distance between crests) and amplitude (height of the wave). Each component wave has a determinate wavelength, but no sense can be made of their "locations" in space (i.e., "position" is indeterminate). If the component waves are added together, the result is the overall waveform on the right, which is called a wave packet. The wave packet that is shown is more localized than any of the individual components—that is, it has a more determinate sense of location in space (though not completely determinate, but there is some sense of it being localized near the center). This wave packet is only "semi-localized" in space because it is the result of adding together only a relatively small number of waves (seven, in this case). The more component waves—monochromatic waves of different wavelengths—are added together, the more localized the wave packet becomes in space. In the limit in which an infinite number of component waves are added together, the wave packet is sharply peaked (with no fringes off to the side). In this limit, position is determinate, and there is no sense whatsoever of what wavelength means. The complementary relationship between the position and wavelength is a general characteristic of waves. The more well-defined the spatial localization, the less well-defined the wavelength, and vice versa. (This general feature of waves is what a Fourier transformation expresses mathematically.) Hence this illustration depicts the general character of the complementary (mutually exclusive) nature of the relationship between position and momentum (which is related to the wavelength through de Broglie's equation: wavelength equals Planck's constant divided by momentum). *Illustration by Nicolle Rager Fuller for the author.*

Notice that if we combine the wave-particle duality relation (1), $p\,\lambda = h$, where $\lambda = 2\pi/k$, with (superposition) equation (2a), we can rewrite the trade-off in limited definability between position, x, and wave number, k, in terms of position, x, and momentum, p, as

$$\Delta x\,\Delta p \geq \hbar/2 \qquad (2)$$

where $\hbar \equiv h/2\pi$. This inequality is instantly recognizable to every student of physics: it is what is known as the "uncertainty relation"—the mathematical expression of the uncertainty principle. However, this is *not* Heisenberg's uncertainty principle: there has been no analysis based on the idea that measurements entail disturbances; there has been no mention of a disturbance whatsoever. Rather, *what has been derived here is Bohr's "indeterminacy principle," which is a quantitative expression of complementarity.*[70]

It is important to keep in mind the distinction between Bohr's "indeterminacy principle" and Heisenberg's "uncertainty principle." While formally they may look identical, their meanings are not the same (in particular, Bohr and Heisenberg attribute different meanings to the mathematical symbol Δ). This is also true of other reciprocal relationships, such as the energy-time uncertainty or indeterminacy relations, which again have the same form, $\Delta E\,\Delta t \geq \hbar/2$, but different meanings. Bohr has the following to say about the position-momentum and energy-time reciprocity relations (which are identified in Bohr's paper as "relations [2]"):

> The content of the relations (2) may be summarized in the statement that according to the quantum theory a general reciprocal relation exists between the maximum sharpness of *definition* of the space-time and energy-momentum vectors associated with the individuals [particles]. This circumstance may be regarded as *a simple symbolic expression for the complementary nature* of the space-time description and the claims of causality. (Bohr 1963a [1927 essay], 60; italics mine)

Bohr is quite explicit here: relations (2) are a *quantitative statement of position-momentum and energy-time complementarity.*[71] And what is at issue for Bohr is clearly the "sharpness of definition" of concepts (like "position"), which within our classical worldview we have previously taken for granted to have well-defined meanings independently of any experimental context, but from the perspective of quantum physics must be understood as semantically determinate only for a given experimental arrangement.[72] This is not at all what Heisenberg has in mind in his description of the "uncertainty relations" as he derives them. Indeed, Bohr emphasizes this difference in his paper's next section, where he details the mistaken argument of Heisenberg:

> The essence of [Heisenberg's argument in his derivation of the uncertainty principle] is the inevitability of the quantum postulate in the estimation of the *possibilities of measurement.* A closer investigation of the *possibilities of definition* would still seem necessary in order to bring out the general complementary character of the description. Indeed, a discontinuous change of energy and momentum [i.e., a disturbance] during observation could *not* prevent us from ascribing accurate values to the space-time co-ordinates, as well as to the momentum-energy components before and after the process. *The reciprocal [indeterminacy] which always affects the values of these quantities is*, as will be clear from the preceding analysis, *essentially an outcome of the limited accuracy with which changes in energy and momentum can be defined*, when the wave-fields used for the determination of the space-time co-ordinates are sufficiently small. (Bohr 1963b [1927 essay], 63; italics mine)

Bohr points out that Heisenberg's derivation of the "uncertainty relations" relies solely on the quantum postulate and the notion of *disturbance*, and that, in fact, this is *not* sufficient to derive the reciprocal relation he proposes. Furthermore, as discussed at length in chapter 3, Heisenberg interprets these relations in terms of what one can *know* upon measurement: "The more precisely the position is determined, the less precisely the momentum is known, and conversely" (Heisenberg, from his paper on the uncertainty relations). Following a heated discussion wherein Bohr offers an important criticism of Heisenberg's analysis, Heisenberg acquiesces to Bohr's point of view. Though it is little discussed, Heisenberg includes an admission of these important shortcomings of his analysis in a postscript to his famous uncertainty paper. In an important sense, this postscript constitutes an undoing of the analysis that he presents in the body of the text, and yet this erroneous analysis has become the standard exposition on the reciprocity relations. The uncertainty principle continues to be taught to students and spoken of by physicists and nonphysicists in accord with Heisenberg's account when by his own admission his account had been based on a fundamental error.[73] Ironically, there is no mention of Bohr's account of the reciprocity relations, that is, the indeterminacy principle. Indeed, if Bohr's contributions to these discussions are mentioned at all, it is usually with a historically respectful nod to complementarity; but even this is seldom mentioned anymore.[74]

Let's take a moment to reiterate the nature of the disagreement. Bohr rejects Heisenberg's suggestion that what is at issue is a *disturbance* created in the act of measurement and that this alleged *disturbance* limits our *knowledge* of presumably (always already) well-defined variables or attributes of the object being measured. Instead, Bohr insists that what is at issue are *the very possibilities for definition of the concepts* and *the determinateness of the properties and boundaries of the "object,"* which depend on the specific nature of the experimental arrangement. That is, Bohr offers an *ontic-semantic interpretation* of the reciprocity relations, in contrast to Heisenberg's (admittedly incorrect) *epistemic* interpretation.

The distinction between Bohr's "indeterminacy principle" (a quantitative statement of complementarity) and Heisenberg's "uncertainty principle" is of great significance, and we cannot afford to lose track of this difference in the discussions of relevant experiments that follow. This distinction is not "merely" of historical interest or philosophical interest but, as we will see, has important implications for the physics as well. Consequently, I have tried to be careful in selecting the appropriate term—"indeterminacy" or "uncertainty"—throughout, and the reader is advised to note the important difference being marked.

3b. Which-path experiments

Bohr's 1935 reply to the paper by Einstein, Podolsky, and Rosen includes an in-depth discussion of the two-slit experiment along with the "which-path" (or "which-slit") option of having the slit(s) mounted on a movable diaphragm (see my earlier discussion). Bohr argues that there is a complementary relationship between using an experimental arrangement that can be used to determine which-path information—that is, information about which particular slit a particle travels through—and the existence of an interference pattern on the fixed detecting screen: "We are presented here with a choice of *either* tracing the path of a particle *or* observing interference effects" (Bohr 1963b [1935 essay], 46).[75] In this subsection, I will discuss several different realizations, both theoretical and experimental, of the famous which-path gedanken experiment. In particular, we will have an opportunity to empirically address the question of whether a disturbance (Heisenberg's position) or an ontic-semantic determination (Bohr's position) is at issue.

The focus of the debate between Einstein and Bohr was whether or not it was possible to determine which-path information without disturbing the interference pattern. As a result, Bohr and Einstein focused only on two limit points of a continuous range of possibilities. They did not concern themselves with the question of the quantitative nature of the trade-off between the determination of which-path information and the determinate delineation of an interference pattern if we were, say, only 80% sure of which slit the particle travels through. But it is an interesting question to contemplate, and a rather unexpected result follows.

What if we were, say, only 80% sure that a particle had gone through the lower slit? For example, what if the diaphragm itself had some initial downward momentum; would it not be possible to draw the wrong conclusion about which slit the particle passed through? Isn't there some probability that the diaphragm could have downward momentum while having gone through the upper slit instead? How much of the interference pattern would be retained if the determination of which-slit information were only approximate, rather than completely certain? In 1979 Wootters and Zurek examined this possibility in detail and were able to give a quantitative statement of the relationship between the extent of partial path determination and the extent of partial "smudging" of the interference pattern. That is, as has been much discussed, if the path information is determined with complete certainty (100%), no interference pattern is manifest; and conversely if the path is completely indeterminate, then an interference pattern with full definition (i.e., complete sharpness) appears (i.e., the two "limit points" discussed by Einstein and Bohr). What Wootters and Zurek explore is the range of possibilities between these two extremes. They find that there exists a continuum of possibilities, "partial wave–partial particle" behaviors, or "intermediate particle-wave behavior."

One might wonder, then, if the results of Wootters and Zurek are not in direct conflict with Bohr's principle of complementarity. As they invite their readers to consider, "Have we not succeeded in observing both particlelike and wavelike properties of the same photon?" (Wootters and Zurek 1979, 476). Wootters and Zurek answer their own question in the negative, pointing out that the notion of "partial wave–partial particle" behavior does not contradict the principle of complementarity, but rather what is at issue is the fact that "a correlation between . . . the measured value of the [movable] plate's momentum . . . and . . . the particle interference pattern—seems inescapable" (477). In other words, there is a necessary trade-off between the quality or definition of the interference pattern and which-path information.[76] Hence Bohr's principle of complementarity is further affirmed by their result that there is a continuous trade-off between particle and wave behaviors; the more it behaves like one, the less it behaves like the other:

> Let us conclude . . . with a clear statement of the complementarity principle in the language of information theory, as it applies to the double-slit experiment. The sharpness of the interference pattern can be regarded as a measure

of how wavelike the light is, and the amount of information we have obtained about the photon's trajectories can be regarded as a measure of how particle-like it is. The . . . inequality [derived using an information-theoretical approach] is thus a precise statement of the following fact: The more clearly we wish to observe the wave nature of light, the more information we must give up about its particle properties. (Wootters and Zurek 1979, 481–82)

In good Bohrian fashion, they offer a precise meaning for the notions of "wave" and "particle" as they apply to the specific situation at hand.[77] On the basis of their analysis, Wootters and Zurek derive "a quantitative statement of Bohr's principle" (as their title states) for the specific case of the recoiling-slit experiment. They confirm the point that Bohr emphasized: the notions of "wave" and "particle" are *not* simultaneously determinate. The results of Wootters and Zurek bring to light the continuous trade-off between interference and which-slit information or between what is sometimes called "fringe visibility" and "distinguishability," that is, between wave and particle behaviors and the appropriateness of wave and particle descriptions, in complete agreement with Bohr's notion of complementarity.[78]

Accounts of the findings of Wootters and Zurek speak of their results as a generalization of Bohr's principle of complementarity, implying that Bohr's principle applies only to extreme cases of complete determination of wave characteristics at the expense of any determination of particle characteristics and vice versa. While it is true that the elegant paper of Wootters and Zurek explores the full range of the continuous trade-off between wave and particle behaviors for the two-slit experiment in a way that neither Einstein nor Bohr touched on in their debate, it is a mischaracterization to say that Bohr's principle of complementarity, as he stated it, encompasses only the limit cases.[79] Let's return to Bohr's own quantitative expression of complementarity—the "indeterminacy principle."

Notice that relations (2) and (2a) include the possibility of such "intermediate" behavior. Indeed, such "intermediate" behavior with respect to the definability of "waves" and "particles" is nothing different than the "intermediate" definability of "position" and "momentum" that we have grown more accustomed to. That is, although it is common to hear it said that one cannot simultaneously determine position and momentum, this rather off-hand way of putting it is more rigorously stated in terms of the *continuous* trade-off between the determination of position and momentum—that is, one *can to a degree* define both the position and momentum simultaneously, but *not* both *sharply* at once. The same holds for waves and particles. The

principle isn't restricted to the limit points; it's just that it is usually stated in its starkest form as a choice between one and the other.

While the fact of a continuous trade-off between particle and wave behaviors is not surprising in and of itself, what is surprising is the precise quantitative relationship that Wootters and Zurek find for the case of the recoiling-slit experiment: what they find is that the interference pattern isn't too badly smeared, or washed out, even when there is nearly certain information about which path the particle traverses. One might have thought that being nearly certain about the which-path information would almost completely obliterate the interference pattern, but this is not the case.

Quantitative statements of Bohr's principle of complementarity have been confirmed experimentally by the Rochester group of Wang, Zou, and Mandel (1991), among others.[80] In particular, the Rochester group was able to confirm the quantitative relationship derived by Wootters and Zurek. Additionally, in the course of their experiment, they noticed something remarkable:

> The disappearance of the interference pattern here is *not* the result of a large uncontrollable *disturbance* . . . in the spirit of the Heisenberg γ-ray microscope, but simply as a consequence of the fact that the two possible photon paths . . . have become distinguish*able*. . . . Whether or not this auxiliary measurement . . . is *actually* made . . . appears to make no difference. It is sufficient that it *could* be made, and that the photon path would then be identifi*able*, *in principle*, for the interference to be wiped out. (Zou et al. 1991, 321; italics mine)

In other words, *all that is required to degrade the interference pattern is the possibility of distinguishing paths*.[81] That is, as Bohr had emphasized in his criticism of both Heisenberg's derivation and interpretation of the uncertainty relations and the EPR analysis, *what is at issue is not the question of a disturbance but rather the "possibilities of definition" of the variables in question*.

Additional theoretical analysis by Jaeger, Shimony, and Vaidman on complementarity further confirms this remarkable finding:

> It is also important to emphasize that the quantity D(P) is *distinguishability*, and the suffix "ability," connoting physical possibility, is crucial. The limitation upon fringe visibility . . . is not imposed by the actual information that the observer has extracted concerning the particles of interest, but in the information that could *in principle* be extracted within the constraints established by the preparation. (Jaeger et al. 1995, 51; italics mine)

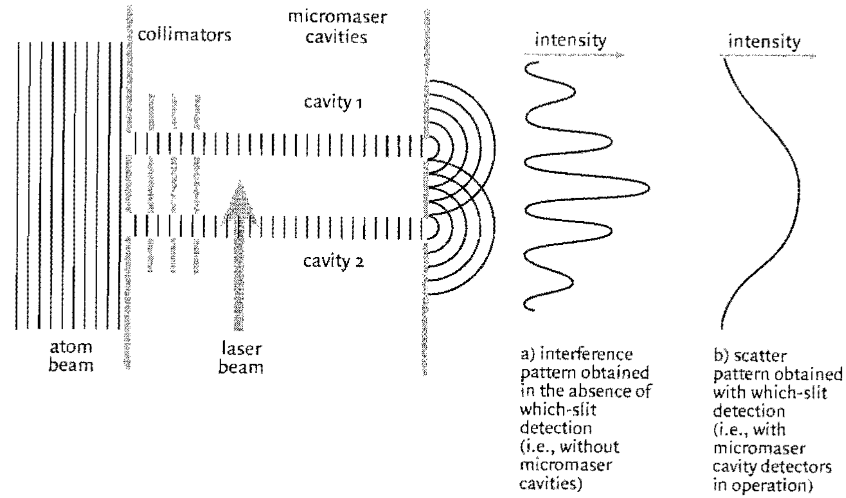
This important finding, like the BKS theorem, shows that what matters is "contextuality"—the conditions of possibility of definition—rather than the actual measurement itself. Since it has been confirmed experimentally that the interference pattern disappears without any which-path measurement having actually been performed—but *just by the mere possibility of distinguishing paths*—these findings offer a clear challenge to any explanation of the destruction of the interference pattern that relies on a mechanical disturbance as its causal mechanism.

These findings lend further credence to the key point that Bohr raises in his criticism of the EPR paper. Recall that Bohr emphasized that "there is in a case like that just considered [i.e., the EPR example] no question [not even in principle] of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure [when we choose what to observe]. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*" (1998 [1935 essay], 80; italics in original).[82]

Using the latest advances in quantum optics, such as micromaser technologies and laser cooling, Scully et al. (1989, 1991) further explore the question of the cause of the destruction of the interference pattern in which-path experiments. They cleverly devise a method for obtaining which-path information that is specifically designed to avoid any disturbance of (the center-of-mass momentum of) the atoms that are the source particles for this two-slit experiment. In other words, it was their intention in designing the experiment to eliminate any possibility that the causal mechanism behind the destruction of the interference pattern could be attributed to a disturbance of the kind Heisenberg mentions in the gamma-ray microscope example of the uncertainty principle.

The basic idea behind the elegant experiment proposed by Scully et al. is the following (see figure 28). Two collimated beams of atoms are directed at two micromaser cavities that are positioned directly in front of the two-slit diffraction grating. Before the atoms reach the cavities, a laser beam is used to excite the atoms to a higher energy state. The micromaser cavities are designed in such a way that when the atom enters the cavity it will (with 100% probability) decay to a lower energy state and emit a photon into the cavity, thereby leaving a physical trace that marks which-path information. The de-excited atoms then pass out of the cavity, go through the two-slit diffraction grating, and are detected on a fixed screen.

Scully et al. perform a detailed calculation to show that the manipulation of the internal degrees of freedom of the atom—that is, the excitation and



28 Diagram of the experiment of Scully et al. A beam of atoms passes through a set of collimators. The laser beam put the atoms into an excited state that will decay with 100% probability in whichever micromaser cavity it passes through, leaving behind in the cavity a telltale photon that marks which cavity it passed through. Crucially, the mark is left behind without in any way disturbing the forward momentum of the atoms, which continue on their way toward the double slits and eventually land somewhere on the detection screen (i.e., the atom leaves some kind of mark on the detection screen). Hence, in this way, the micromaser cavities can be used to detect which-path information without disturbing the atoms; that's the beauty of this experiment. In the absence of the which-path detection apparatus, the result is the usual interference pattern shown in graph a. With the which-path detection apparatus in operation, the interference pattern is destroyed, and now a scatter pattern as shown in graph b results. *Illustration by Nicolle Rager Fuller for the author.*

de-excitation—does not disturb the (external/"center-of-mass") motion of the atom. Therefore, by this method, they can track which-path information according to whether or not a photon is left behind in one or the other of two micromaser cavities placed just in front of the two slits, without causing any disturbance to the motion of the atom.

What is the result? Despite the lack of disturbance, the experimenters nonetheless confirm the existence of which-path–interference complementarity. That is, what is evident is a trade-off between which-path information and interference, as Bohr predicted. Since there is no disturbance in this case (the experiment was designed to exclude it), the experimenters therefore conclude that the Heisenberg uncertainty cannot be the source of the destruction of the interference pattern, and they search for an alternative cause for the "enforcement" of which-path–interference complementarity. The source of complementarity that they suggest is the correlation "between the measuring apparatus and the systems being observed," that is, the entanglement of the "object of observation" and the "agencies of observation":

> We have found a way . . . to obtain which-path or particle-like information without scattering or otherwise introducing large uncontrolled phase factors [i.e., disturbances] in to the interfering beams. To be sure, we find that the interference fringes disappear once we have which-path information, but we conclude that *this disappearance originates in correlations between the measuring apparatus and the systems being observed.* The principle of complementarity is manifest although the position-momentum uncertainty relations plays no role. (Scully et al. 1991, 111; italics mine)

Let's recall what Bohr says about the source of complementarity. Bohr (1949) concludes his discussion of the recoiling-slit gedanken experiment with the following summary:

> This point is of great logical consequence, since it is only the circumstance that we are presented with a choice of *either* tracing the path of a particle *or* observing interference effects, which allows us to escape from the paradoxical necessity of concluding that the behaviour of an electron or a photon should depend on the presence of a slit in the diaphragm through which it could be proved not to pass. We have here to do with a typical example of how the complementary phenomena appear under mutually exclusive experimental arrangements . . . and *we are just faced with the impossibility, in the analysis of quantum effects, of drawing any sharp separation between an independent behaviour of atomic objects and their interaction with the measuring instruments which serve to define the conditions under which the phenomena occur.* (Bohr 1963b [1949 essay], 46–47; italics mine)

What is the root of complementarity? It is the impossibility of drawing any sharp separation between an independent behavior of atomic objects and their interaction with the measuring instruments, which serve to define the conditions under which the phenomena occur. In other words, the inseparability of objects and agencies of observation is the basis for complementarity.

Recall that on the basis of my agential realist elaboration of the implicit ontological dimensions of Bohr's complementarity framework, phenomena do not merely mark the epistemological inseparability of observer and observed; rather, *phenomena are the ontological inseparability of agentially intra-acting "components."*[83] That is, in the case in question, phenomena are the ontological entanglement of objects and agencies of observation. Hence it is the ontological inseparability or entanglement of the object and the agencies of observation that is the basis for complementarity. This can be contrasted with Schrödinger's notion of entanglement, which is explicitly epistemic (what is entangled is our knowledge of events). By contrast, Bohr understands entanglements in ontological terms (what is entangled are the "components" of phenomena). For Bohr, phenomena—entanglements of objects and agencies of observation—constitute physical reality; phenomena (not independent objects) are the objective referent of measured properties. *Complementarity is an ontic (not merely an epistemic) principle.*

The experiment suggested by Scully et al. is an elegant contribution to the understanding of deep questions in quantum physics, but there is something peculiar in the framing of their paper. The abstract to their review article in the journal *Nature* suggests that the usual mechanism of enforcement of complementarity is the uncertainty principle, which does not apply in this case because the specific design of their experiment excludes any disturbance, and so the mechanism of enforcement, they suggest, is the entanglement of the measuring instrument and the object.[84] Since I have been emphasizing the important differences between Bohr's indeterminacy relations and Heisenberg's uncertainty relations, the reader may find this claim by Scully et al. that complementarity depends on the uncertainty relations puzzling at best (and their explanation for the enforcement of complementarity in this specific case rather obvious given Bohr's own analysis).[85] What would it mean for the uncertainty principle to be the mechanism of enforcement of complementarity? Don't uncertainty and complementarity mark distinct interpretations? How can one be understood as the basis for the other? To be fair to Scully et al., we need to back up for a moment and understand the nature of the current episteme that Scully et al. are working in or against, for their important intervention is offered in light of a specific, widely held paradigm, which differs in substantial ways from the one that I offer here. For many physicists, including researchers who are actively investigating Bohr's principle of complementarity, there is a persistent (but mistaken) belief that Bohr argues for complementarity on the basis of Heisenberg's uncertainty principle. The source of this mistaken belief seems to be in the common (and inaccurate) retellings of the argument that Bohr employs to defeat Einstein's proposal to use the recoiling-slit experiment to gather which-path information without causing any disturbance that would destroy the interference pattern.[86] Indeed, this misunderstanding is so well accepted that the work of Scully et al. has spawned a debate about which principle is more essential—the uncertainty principle or the principle of complementarity.[87] But the issue of priority is a red herring, for not only should the familiar reciprocity relations be understood more appropriately as the indeterminacy principle (not the uncertainty principle), as I have argued, but Bohr's indeterminacy principle is itself a quantitative statement of complementarity! In appendix B, I consider Bohr's response to Einstein in detail and demonstrate that Bohr invokes his quantitative expression of indeterminacy (not Heisenberg's uncertainty principle) to refute Einstein's challenge. It is the fact that the reciprocity relations are invariably taken to be the uncertainty principle (and that Bohr's indeterminacy principle is not appropriately acknowledged) that is the source of this misunderstanding.

In recent years there have been many direct experimental tests of complementarity. While results in science are never incontrovertible, but rather are always open to question and to multiple interpretations and to the possibility of reinterpretation in the face of new theoretical and empirical findings, these experimental findings offer direct evidence on behalf of several main tenets of Bohr's philosophy-physics, including the following:[88]

—complementarity (dashing Einstein's hopes that it is possible to obtain which-path information without destroying the interference pattern);
—understanding complementarity as a matter of entanglement/inseparability ("contextuality") rather than disturbance (distinguishing the views of Bohr and Heisenberg);
—understanding that what is at issue is the nature of specific experimental arrangement—the conditions for the possibilities of ontic-semantic determinacy—and not actual observations per se (see hereafter), as empirically supported by the fact that what is required for the loss of interference is not the observation of which-path information but the very *possibility* of distinguishing paths.

4 COMPLEMENTARITY III: QUANTUM ERASERS—ENTANGLEMENTS RULE!

If the loss of an interference pattern in a which-path detection experiment is due to the *entanglement* of the object and the measuring instrument, rather than a *disturbance* (e.g., uncontrollable or random scattering or other stochastic perturbations), might it not be possible to restore the interference pattern by "undoing" or "erasing" the which-path detection? That is, might it be possible to retrieve the coherence information contained in the super-

position, since it has not been destroyed or lost by an uncontrollable disruption, but rather has simply been "redistributed" to different parts of the system through their mutual entanglement? For example, what if we were to "erase" the which-path information so that the paths were once again made to be indistinguishable; might not the interference pattern return? If this didn't happen, we might not be too disappointed; we'd probably think, "Oh well, that was a cool idea, but I guess I wasn't clever enough about finding the correlation information that still lies in wait somewhere in this entanglement." But what if we could? What if we did? What if it were possible to perform an actual "quantum eraser" experiment?[89] Well, it turns out that it is possible. And it gets better: it turns out that not only is it possible to restore the interference pattern by erasing the which-path information (if we are indeed clever enough to measure the right variables to find the correlation contained in the entanglement), but we can decide whether or not to erase the which-path information *after the atom has passed through the slits and registered its mark on the screen*. That is, we can wait until the atom has passed through the entire apparatus and only then decide if we want to erase the which-path information in the micromaser cavities—in which case it is still possible to retrieve an interference pattern! It seems unbelievable, but it's true.[90] That is, it is indeed possible to perform a quantum eraser experiment in "delayed choice" mode.[91] How can this be? And what does it mean?

First, what does it mean to "erase" the which-path information? Consider the two-slit experiment with micromaser which-path detectors of Scully et. al. (1991) discussed in the previous section. The experiment is specifically designed to produce a record of each atom's which-path information: in particular, by the time an atom has passed through the double slit diffraction grating it has left behind a telltale photon in either the upper or lower cavity, depending on whether the atom took the upper or lower path through the diffraction grating. The presence of a photon in one of the cavities thereby indicates which slit the atom passed through. How might we modify the original apparatus in a way that will enable us to erase the which-path information? One way to do this is to replace the wall between the upper and lower cavities with a photodetector-shutter system: we remove the dividing wall and place a photodetector between the two cavities, and then shield it from exposure to each cavity by placing shutters in front of the photodetector on both sides. If the shutters remain closed the photodetector is blocked and the photon remains in whichever cavity it was in—it's as if the wall were still there. But if the shutters are opened (on both sides at once) and the photon left behind in either the upper or lower cavity is absorbed by the photodetector we no longer have information about which cavity the photon was in. The which-path information is thereby "erased" (see figure 29 for a sketch of the modified apparatus).

According to Bohr, if we use an apparatus that does not enable us to distinguish which slit an atom goes through on its way to the screen then we should observe an interference pattern. But does this hold in the case in question in which the which-path information is erased? This would seem to require that each atom "know" what our decision is going to be—to leave the shutters closed or open them—*before* it hits the screen. But in fact, Bohr's prediction seems to hold even if we wait until *after each atom has already hit the screen* before we decide whether or not to open the shutters. That is, even in a case like this we should still observe an interference pattern since there is no possibility of distinguishing which slit each atom passed through. But if the experimenter can decide whether or not an interference pattern will result by deciding whether or not to erase the which path information long after each atom has already hit the screen then it seems the experimenter has control over the past. How can this be? Perhaps we have come to the limit of Bohr's principle of complementarity.

Scully et al. do the quantum mechanical calculation for a quantum eraser experiment performed in "delayed choice" mode. What they find is that in fact Bohr's prediction holds: if the which-path information is erased an interference pattern results, even if the experiment is performed in delayed choice mode, that is, even if the experimenter waits for each atom to hit the screen before opening the shutters (or not). How can we understand this result? And what form would it take? Clearly the interference pattern will *not* be evident in simply looking at the screen since each atom already makes its mark before the shutters are opened. Physicists are quite comfortable with the fact that, generally speaking, the results don't simply announce themselves; rather, one has to analyze the data some way. In this case the task before us is to figure out what we should be looking at.

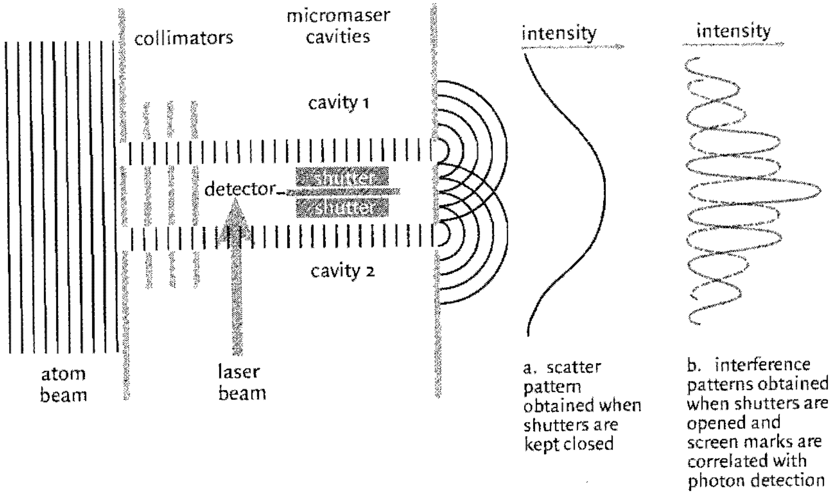
How do we figure this out? First of all, it is important to know that when the shutters are opened there is a 50% probability that the photon (left in either the upper or lower cavity) will be absorbed by the photodetector.[92] That is, half the time which-path information will be erased and half of the time it won't. This means that the scatter pattern we will inevitably find on the screen is the trace of two different kinds of events: those that have their which-path information erased and those that don't. It's possible to separate these out by correlating the individual marks left on the screen with the results of the photodetector: all we have to do is keep track of whether or not

the which-path information was erased (i.e., it was detected by the photodetector) for each atom as it hits the screen. That is, we identify each of the marks on the screen with a "yes" or a "no" depending on whether or not the which-path information was erased or not (i.e., whether or not the photon was detected or not). Having kept track of the results in this way we can then look at all the "yes" data points separately from the "no" data points.

Figure 29 shows two different representations of the data. The one labeled "a" shows the full set of data points. This is just what we'd see on the screen without making any effort to separate out those points that correspond to events for which the which-path information was erased and those that weren't. Whereas, the representation labeled "b" makes precisely this distinction. There are two separate graphs shown in "b": the data plotted with a solid line is marked out by those points on the screen for which we no longer have which-path information, that is, the which-path information was erased (i.e., the corresponding photons were detected); and the dashed line shows those marks on the screen for which their which-path information was not erased (i.e., no photon detected). The two curves together make up the overall scatter pattern shown in "a" (i.e., taken together they account for all the data points).

Now we're in a position to find out what happens when the which-path information is erased (because we now have a way of attending to only those traces left on the screen for which the photon was absorbed). The crucial plot here is the one with the solid line in "b." These are the data points that correspond to those atoms whose which-path information was erased, the very ones we're interested in. And what do we see? An interference pattern, just as Bohr predicted! How are we to understand this remarkable result? Is the experimenter really able to change the past?

Had Bohr been confronted with the idea of a quantum eraser experiment he might have well started his explanation with a statement echoing his response to Einstein in the face of the EPR challenge: an interference pattern would surely result from the erasure of which-path information even though the atoms are far removed from the micromaser cavities since "of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation [i.e., on the atom's center-of-mass wave function] during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*" (1998 [1935 essay], 80). The intention of such a response would be to focus our attention on the phenomena in question. Or as



29 Quantum eraser experiment using a variation of the micromaser detection system of Scully et al. In this variant of the experiment shown in figure 28, a detector replaces the wall separating the cavities, and shutters are placed on either side of the detector. The combined shutter and photon detection system makes possible the erasure of which-slit information. If the shutters remain closed, the apparatus is as in figure 28, and the result is the scatter pattern ("particle" pattern) shown by graph b in figure 28 and graph a in the present figure. On the other hand, we can operate this experiment in eraser mode by opening the shutters. If the shutters are opened there is a 50% chance that the photon will be detected (i.e., absorbed at the detector between the cavities), and a 50% chance that it won't be detected. (Now, before we look at the results, recall that there are two sets of marks to keep track of in the experiment: the photon that is left behind in one of the cavities and the mark the atom leaves on the detecting screen.) If we monitor the atoms producing the photons that are subsequently detected by the photon detector (i.e., those that have their which-path information erased), the result would be an interference pattern shown by the solid line indicated in graph b in the diagram. If we monitor the atoms producing the photons that are not detected, instead we get an interference pattern shifted relative to the other one (indicated by the curve with the dashed line in graph b). If no distinction is made and all atoms are counted just the same, then the two interference patterns (solid and dashed lines in graph b) combine to form an overall scatter pattern (eliding the existence of the two interference patterns and the entanglements they indicate). *Illustration by Nicolle Rager Fuller for the author.*

one group of experimenters who have demonstrated that it is possible to perform quantum eraser experiments in delayed choice mode puts it, "to correctly understand the results, one must adhere to Bohr's dictum to consider the *entire* experimental system" (Kwiat et. al., 1994, 63, original emphasis). Another experimental group writes: "In conclusion, our results corroborate Bohr's view that the whole experimental setup determines the possible experimental predictions" (Herzog et. al., 1995, 3037).

In other words, the quantum eraser experiment confirms Bohr's central point that the objects and the agencies of observation are inseparable parts of a single phenomenon. In particular, the atom is not a separate object but rather an inseparable part of the phenomenon (that includes the micromaser cavities, the photodetector-shutter system, the double slit diffraction grating, and the screen among other elements), and the paradoxical aspects of the findings result from the mistaken identification of an abstract individual with the objective referent when what is at issue is the phenomenon. Indeed, it is the quantum entanglement between the "object" and the "agencies of observation," in this case, between the atom and the apparatus that is precisely what we need to attend to in making the interference pattern evident. Once again we see evidence for the ontological priority of phenomena over objects. If one focuses on abstract individual entities the result is an utter mystery, we cannot account for the seemingly impossible behavior of the atoms. It's not that the experimenter changes a past that had already been present or that atoms fall in line with a new future simply by erasing information. The point is that the past was never simply there to begin with and the future is not simply what will unfold; the "past" and the "future" are iteratively reworked and enfolded through the iterative practices of spacetimemattering—including the which-slit detection and the subsequent erasure of which-slit information—all are *one phenomenon*. There is no spooky-action-at-a-distance coordination between individual particles separated in space or individual events separated in time. Space and time are phenomenal, that is, they are intra-actively produced in the making of phenomena; neither space nor time exist as determinate givens outside of phenomena.

What leads to this paradox of a changing past? As in the case of the EPR challenge, of the question of how individual entities can engage in instantaneous communication (that is, "know" what is going on with each other as soon as something happens) arises out of a mistaken belief in metaphysical individualism. That is, the paradox arises out of the mistaken assumption that there are individually determinate entities from the outset; this assumption, which is the basis for classical physics, is precisely what is being called into question here. As we have seen, in the EPR case the entities are not separately determinate individuals but rather inseparable parts of a single phenomenon. In particular, there are no preexisting-individually-determinate-entities-with-determinate-spatial-positions-communicating-instantaneously-at-some-remove-from-one-another outside of a phenomenon that determinately resolves the boundaries and properties of the entangled components in a way that gives meaning to the notion of individual. Indeed, "individual" is ontologically and semantically indeterminate in the absence of an apparatus that resolves the inherent indeterminacy in a way that makes this notion intelligible.

Similarly, in the case of the quantum eraser experiment the question of how it is possible to influence events that have already occurred in the past (i.e., whether or not the atom will have gone through a single slit or both slits at once by performing a measurement after the atom has already passed through the diffraction grating) arises when we make certain assumptions about the nature of space, time, and matter. Once again metaphysical individualism, including the assumption that material objects occupy a single position in a preexisting space at a preexisting moment of time, is the basis of the paradox. Scully et al. remark that once the shutters are opened and the photon is absorbed by the photodetector the "memory of passage" can be said to have been erased. It is also common in discussions of the quantum eraser experiment to see references to the notion that with the erasure of which-path information the interference pattern is "recovered." But as we have seen the original interference pattern is not recovered; rather a new interference pattern, one that takes a very different form (than an interference pattern that is evident in a two-slit experiment that was never equipped with a which-path detector) and is revealed only through an appropriate sorting procedure, results from the "erasure" and the procedure of accounting for the entanglement. Indeed, in this regard it seems clear that the memory of the event has not been erased, at least not in the usual senses of the terms "memory" and "erase"; on the contrary, in an important sense it seems evident that the observed phenomenon holds the memory of the fact that the which-path information was first determined and then made to be indeterminate once more through an appropriate modification of the apparatus. "Erasure" is therefore a misnomer. The important point is that time, like space and matter, is phenomenonal (i.e., time is not an external parameter but rather is an integral aspect of phenomena). As a result of the iterative nature of intra-active practices that constitute phenomena, the "past" and the "future" are iteratively reconfigured and enfolded through one another: phenomena cannot be located in space and time; rather, phenomena are material entanglements that "extend" across different spaces and times.

In summary, the quantum eraser experiment not only supports Bohr's interpretation over Heisenberg's, that is, the explanation based on indeterminacy rather than uncertainty, but it confirms *the* centerpiece of Bohr's interpretation: the inseparability of the object from the agencies of observation. Furthermore, these experiments demonstrate that measurements *extend* rather than resolve (collapse) entanglements, as will be discussed hereafter.

REAL AND IMAGINED LIMITATIONS OF BOHR'S INTERPRETATION

In this section I clarify important issues concerning Bohr's interpretation of quantum mechanics and sort out possible legitimate objections from a host of misunderstandings.

1 DOES BOHR ANSWER EINSTEIN'S REALISM WITH ANTIREALISM? QUESTIONS OF OBJECTIVITY AND SEPARABILITY

There seems to be a strong prejudice among philosophers, historians, and physicists in favor of ascribing realism to Einstein and antirealism to Bohr. But the fact of the matter is that neither Einstein nor Bohr is easily saddled with either of these philosophical positions, at least not in their traditional forms. Arthur Fine (1986) argues that Einstein's philosophical position does not fit any of the usual realist positions. Fine suggests, rather, that "if we understand Einstein in a way that he asks us to, his own realist-sounding language maps out a position closer to constructive empiricism than to either 'metaphysical realism' or 'scientific realism'" (108). Indeed, Einstein's positivist (i.e., radical empiricist) leanings are well documented.[93] By the same token, I am not alone in arguing that Bohr's views are more accurately described in realist than antirealist terms.[94] Needless to say, Bohr is also not a metaphysical or a scientific realist.

Among the myths that circulate around the realism versus antirealism debates is the belief that realists embrace objectivity while antirealists reject it in favor of some version of subjectivism or even epistemological relativism. But this misconception underestimates the range of realist and antirealist understandings of the notion of objectivity. A quick counterexample may suffice to indicate the extent to which this myth oversimplifies a complex set of issues. For example, the philosophers Ian Hacking and Nancy Cartwright separate entity realism from theory realism. That is, it is possible to maintain a belief in the reality of electrons and other such entities that science brings to light and not subscribe to the realist belief in the correspondence between theoretical terms and physical reality. Realism is not an all-or-nothing affair. Furthermore, "objectivity" is not a monolithic notion. "Objectivity" has a history, and there are often multiple extant meanings at any given time (see, for example, Daston 1999; Lloyd 1996).

As I have argued in earlier chapters, there is an important sense in which the entire realism versus antirealism debate is a red herring.[95] Traditional conceptions of both views are premised on representationalism. Significantly, quantum mechanics challenges the premises of representationalism. Not surprisingly, then, the realism-antirealism opposition distorts important differences between the positions of Bohr and Einstein and discounts the subtleties of each of their views. Rather than attempting to spin out their differences along the realism-antirealism axis, my focus in this section will be on the main point of contention between Bohr and Einstein: the question of separability.[96] (I have already provided a detailed discussion in chapter 3 of important differences between them with regard to the question of objectivity, and I continue this discussion in the next section.)

Questions concerning the existence of Bell-like correlations or the entanglement of states are often referred to in the literature under the rubric of "nonlocality," or by more evocative terms like "spooky-at-a-distance" or "passion-at-a-distance."[97] But if there is some kind of violation of the principle of locality, as these namings imply, what kind is it? Can Bell-like states be used to effect instantaneous communication between Alice and Bob? If so, there would seem to be an inconsistency between quantum theory and the special theory of relativity, since, according to the latter, information cannot travel faster than the speed of light. This issue has been given considerable consideration, and it has been determined that this so-called nonlocality in quantum mechanics does *not* in fact entail the instantaneous transmission of a signal (or information), or any transmission faster than the speed of light, that is, it does not violate the special theory of relativity. So in what sense, if any, is nonlocality an issue?

In the 1980s, Jon Jarrett (1983, 1984) reexamined the assumptions that underlie Bell's inequality. Jarrett determined that Bell's "locality" condition is really the conjunction of two logically independent conditions: (1) locality (in the strong sense of violating the principle of relativity) and (2) "outcome independence."[98] Don Howard, a philosopher of science, argues that "outcome independence" is equivalent to what he calls the "separability" condition, which asserts that "each of the two previously interacting systems in the Bell experiments possesses its own physical state, the joint state being the product of these two separate states" (Howard 1989, 230). In this account, the violation of Bell's inequality is due to the failure of one or both of the following assumptions: separability or locality (232).[99] According to Howard, the Jarrett conditions call into question the existence of a more benign type of nonlocality, sometimes called "quantum nonlocality" (or metaphysical nonlocality, to distinguish it from "physical nonlocality" which is the stronger kind of nonlocality that would violate special relativity), and suggests that the source of what looks like some kind of (weak) nonlocality is actually nonseparability. David Mermin also argues against so-called quantum nonlocality, suggesting that it is nothing more than "fashion at a distance" (1999, 583). Arguing along the same lines as Bohr in his response to Einstein, Podolsky, and Rosen, Mermin suggests that quantum nonlocality is merely an artifact that "arises when one tries to reconcile the *actual* results of specific experiments to the *hypothetical* results of other experiments that might have been performed but were not. . . . Indeed, it is hard to give 'what would have been perceived' any meaning" (Mermin 1998, 761; italics in original). That is, as we will see, for reasons connected to the question of separability, the issue of (quantum) nonlocality is a nonissue for Bohr. Not surprisingly, neither Einstein nor Bohr was willing to give up on locality (in the strong sense). However, they passionately disagreed about the question of separability.

A passage in a letter from Einstein to Max Born, dated March 24, 1948, illuminates some of the key issues for Einstein that lie behind the EPR paradox and what is at issue for him in his commitment to separability:

> I just want to explain what I mean when I say that we should try to hold on to physical reality. . . . That which we conceive as existing ("actual") should somehow be localized in time and space. That is, the real in one part of space, A, should (in theory) somehow "exist" independently of that which is thought of as real in another part of space, B. . . . What is actually present in B should thus not depend upon the type of measurement carried out in the part of space, A; it should also be independent of whether or not, after all, a measurement is made in A. . . . *If one renounces the assumption that what is present in different parts of space has an independent, real existence, then I do not at all see what physics is supposed to describe.* For what is thought to be a "system" is, after all, just conventional, and I *do not see how one is supposed to divide up the world objectively so that one can make statements about its parts.* (Einstein, quoted in Howard 1989, 240–41; italics mine)

But it is just such questions—questions that go to the issue of *the objective referent*—that Bohr saw his epistemological framework as addressing. Perhaps this explains why Bohr could not understand why his previous explanations had not satisfied Einstein; as far as Bohr was concerned, the EPR paper presented nothing new—Bohr had already answered these very issues.[100] For example, Einstein wants to know, if we give up on separability, what we should understand physics as describing. Bohr had already answered: *phenomena* are what physics describes, not some presumably independently existing object (which the failure of separability denies). Einstein wants to know how the "observer" can then be differentiated from the "observed" such that this individuation is made in an objective fashion. Bohr answered that objectivity is not predicated on an inherent or Cartesian cut between the two; rather, what is required for objectivity is an unambiguous and reproducible account of marks on bodies. This requires the intra-active enactment of a "cut" (determined by the larger experimental arrangement) that unambiguously differentiates the "object" (that which "causes" the mark) from the "agencies of observation" (the "effect" or that which receives the mark), thereby constituting a reproducible and unambiguous measurement of one part of the phenomenon by another part (see chapter 3).

In other words, both Einstein and Bohr agree that there must be an objective criterion for individuation so that the question "to what would one ascribe the properties thought to be revealed by those measurements?" can objectively be answered. Einstein says that he can imagine no other criteria than spacetime separability. But Bohr not only can and does propose a different criterion but insists that the delineation of observer and observed be determined by the physics, not by philosophical preconceptions.

Bohr clearly rejects the separability condition: indeed, the very notion of a phenomenon, as Bohr defines it, flies in the face of the separability condition. For Bohr, the quantum postulate and the material embodiment of concepts are at the root of quantum nonseparability (what Bohr often refers to as the "individuality" of phenomena). As I have argued (see chapters 3 and 4), for all his interest in the epistemological lessons of quantum physics, one of Bohr's most important contributions is a new ontology based on his notion of a phenomenon (though he doesn't explicitly articulate the crucial ontological dimensions of his account). Thus Bohr is firm in his rejection of the separability condition and equally adamant about the objective nature of the theory (as safeguarded by complementarity).

By contrast, Einstein maintained a belief in separability as the very condition for the possibility of objectivity. Don Howard suggests that what was at stake for Einstein in his commitment to separability was a combined faith in methodological realism, epistemological conviction in a spectator theory of

knowledge, and theoretical allegiance to the notion of a field.[101] Howard reads Einstein's belief in separability in terms of a literal externality relation, the spatial separation between observer and observed:

> Like so many realists before him, Einstein speaks of the real world which physics aim to describe as the real "external" world, and he does so in such a way as to suggest that the independence of the real—its not being dependent in any significant way on ourselves as observers—is grounded in this "externality." For most other realists this talk of "externality" is at best a suggestive metaphor. But for Einstein, it is no metaphor. "Externality" is a relation of spatial separation, and the separability principle, the principle of "the mutually independent existence of spatially distant things," asserts that any two systems separated by so much as an infinitesimal spatial interval always possess separate states. Once we realize that observer and observed are themselves just previously interacting physical systems, we see that their independence is grounded in the separability principle along with the independence of all other physical systems. (Howard 1985, 192–93)

Bohr and Einstein construe the relation of externality between observer and observed very differently. For Einstein, externality is a relation of spatial separation. For Bohr, on the other hand, the individuation of "observer" from "observed" is not the result of spacetime separability, because one cannot help oneself to spacetime descriptions. Rather, individuation is the result of specific intra-actions that entail the larger material arrangement. In my elaboration of Bohr's account, I argue that objectivity is premised on an agential (or enacted) ontological separability, an individuation-within-and-as-part-of-the-phenomenon enacted in the placement of the cut between "observer" and "observed," rather than an absolute notion of externality. That is, I suggest a strengthening of Bohr's epistemic notion of objectivity, replacing it with an ontological conception that foregrounds the issue of ontological separability, as Einstein would have it, but without grounding it in the problematic criterion of spatial separability (see chapter 3). Indeed, it has become increasingly difficult in recent years to hold to a belief in the separability condition, especially as the evidence builds for the existence of quantum entanglements along with an increasing recognition of their significance in quantum theory. This brings the question of objectivity to the fore once again. The agential realist proposal for maintaining objectivity in the face of the failure of the separability conditions and related questions of objectivity are taken up in more detail in the next section.

2 OBJECTIONS TO BOHR'S ACCOUNT: REAL AND IMAGINED

Specialness is anathema to physics. There is a long-held, principled belief among physicists that the world is ontologically democratic in the sense that everything—every moment in time, every point in space, every direction, every translation or rotation in space or in time or in some abstract phase space, indeed, every change—applies equally for all (for all time, for all space, for all beings) unless there is a specific reason for any particular exception. Universality is a given; particularity needs explanation. Sameness is assumed; difference occurs for a reason. Specialness is an unnatural affair requiring justification. For example, symmetry and uniformity are considered natural states of being, while any existing asymmetry or variation must have a cause. An asymmetrical state is said to have "broken" symmetry, and there is an obligation to provide a mechanism for the symmetry breaking.[102] Similarly there is a principled aversion to granting privileged status to one thing over another without a good reason. Whether, for example, such special status is awarded to human contrivances, such as measurements, over naturally occurring interactions among systems, or to special kinds of measuring devices (e.g., conscious beings) over other physical systems, privileged status provokes unease. Perhaps this is why physicists find any suggestion to the effect that the work they are engaged in is in any way partial to one kind of human over another (whether the distinction is drawn on the grounds of nationality, religion, gender, race, class, or eye color) so downright objectionable, even repugnant. This aversion to specialness also accounts for some of the apprehensiveness toward the so-called Copenhagen interpretation of quantum mechanics.[103]

Giving voice to a general sense of discomfort with both the privileged role of measurement observations and the privileged role of human knowledge in the foundations of quantum mechanics, the physicist David Mermin (1998) writes:

> Why should the scope of physics be restricted to the artificial contrivances we are forced to resort to in our efforts to probe the world? Why should a fundamental theory have to take its meaning from a notion of "measurement" external to the theory itself? Should not the meaning of "measurement" emerge from the theory, rather than the other way around? Should not physics be able to make statements about the unmeasured, unprepared world?
>
> To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation will not exclude the big world outside the laboratory. (756)
>
> There has always been talk to the effect that quantum mechanics describes not the physical world but our knowledge of the physical world. This intrusion of human knowledge into physics is distastefully anthropocentric. (758)

In his usual incisive fashion, Mermin places the focus where it belongs. I agree that Bohr's philosophy-physics is limited by its anthropocentrism. In addressing this difficulty, it is important, however, to distinguish between a principled exclusion of the human, based on the belief that humans have *no place* in a physical theory, and one based on the posthumanist refusal to presume that humans occupy a privileged position in physical theories. Notice that the former conception, the idea that the rightful place of the human is that of an exterior observer, a spectator, removed from the scene of action, is ironically no less wedded to the humanist conception of man than its anthropocentric counterpart. This conception, so familiar to the classical mind-set, presumes that man is a conscious being, apart from all other beings, a separateness that is the classical condition for the possibility of objective knowledge. By contrast, a posthumanist stance does not presume that man occupies a special position inside or outside the realm of natural phenomena or the theory that accounts for them. Rather, making a similar point to Mermin's about measurements, it asks: Should not the "human" be accounted for in terms of the theory and the specific intra-actions from which it emerges, rather than the other way around? In a sense, Bohr shares this posthumanist stance when he remarks that we are a part of that nature we seek to understand; but what he offers with one hand, he takes away with the other.[104]

In this section I address the anthropocentric elements of Bohr's philosophy-physics, not on the basis of any "*a priori* philosophical conception, but . . . on a direct appeal to experiments and measurements" (Bohr 1998 [1935], 73–74), and the requirements of logical consistency, two criteria near and dear to Bohr's heart. But since it is also the case that the nature and degree of Bohr's anthropocentrism are widely misunderstood (as with other aspects of Bohr's philosophy-physics, misreadings abound), it is important to continue our efforts to separate wheat from chaff.

2a. Are measuring devices intrinsically classical systems?

There are special systems that do not obey conventional quantum mechanics, but are "intrinsically classical" in that they produce collapse of the wave functions—or the actualization of the values of quantities. This idea underlies a variety of old and recent attempts to unravel the quantum puzzle, the special systems being, for instance, gravity (Penrose 1989), or minds (Albert and Loewer 1988), or macroscopic systems (Bohr 1949). If we accept this idea, we have to separate reality into two kinds of systems: quantum mechanical systems on the one hand, and special systems on the other. Bohr claims explicitly that we have to renounce giving a full quantum mechanical description of the classical world (Bohr 1949). (Rovelli 1996, 1644)

First of all, it is probably worth repeating several points I made earlier about whether quantum theory requires us to think of the world as separated into two distinct domains. I have emphasized that there is nothing in the theory of quantum mechanics nor is there any empirical evidence that suggests that there are two distinct domains of reality separated at a particular length scale. There is no theoretical basis or empirical evidence for the belief held by some that the laws of quantum mechanics apply only to the restricted domain of microscopic objects and that the laws of classical mechanics apply to the macroscopic domain. On the contrary, the overwhelming empirical success of quantum theory suggests that it is a theory that *supersedes* Newtonian physics.

Furthermore, there is no evidence that Bohr insisted on a restricted domain for the applicability of the quantum theory. Bohr never states that there are two separate domains of being—one classical and one quantum mechanical—where two separate laws of physics operate (as we'll see his views are quite to the contrary). He *does* say that an account of measuring instruments is to be given in classical terms. In particular, he explains that since "all those properties of such agencies, which according to the aim of the measurement, have to be compared with corresponding properties of the object, must be described on classical lines, their quantum mechanical treatment will for this purpose be essentially equivalent with a classical description" (Bohr 1998 [1935 essay], 104). Clearly then Bohr is not saying that the quantum formalism does not apply in the macroscopic domain and is restricted in its applicability to the microscopic world. Furthermore, Bohr emphasizes that "particular elements" of macroscopic instruments (e.g., the movable diaphragm in the which-slit experiment) must be treated quantum mechanically. This point in itself undermines any attempt to attribute a belief in separate physical domains to Bohr (since it is not necessarily the case that all elements of macroscopic instruments behave classically). In fact, this crucial point holds some important clues as to Bohr's thinking

about the constitution of the subject-object distinction and is worth delving into in some detail.

Consider the following passage, which has mistakenly been understood as an insistence by Bohr on the existence of separate domains:

> The main point here is the distinction between the *objects* under investigation and the *measuring instruments* which serve to define, in *classical terms* [my italics], the conditions under which the phenomena appear. (Bohr 1963b [1949 essay], 50)[105]

But this statement is not an exhortation to embrace separate physical domains; on the contrary, the passage continues:

> Incidentally, we may remark that, for the illustration of the preceding considerations [one case discussed is the two-slit experiment with a movable diaphragm], it is not relevant that experiments involving an accurate control of the momentum or energy transfer from atomic particles to heavy bodies like diaphragms and shutters would be very difficult to perform, if practicable at all. It is only decisive that, *in contrast to proper measuring instruments, these bodies* [diaphragms and shutters] *together with the particles would in such a case constitute the system to which the quantum-mechanical formalism has to be applied* [my italics]. As regards the specification of the conditions for any well-defined application of the formalism, it is moreover essential that the *whole experimental arrangement* be taken into account. In fact, the introduction of any further piece of apparatus, like a mirror, in the way of a particle might imply new interference effects essentially influencing the predictions as regards the results to be eventually recorded. (Ibid.)

Here is a clear statement by Bohr that *macroscopic* systems (e.g., movable diaphragms and shutters) are to be accounted for using the quantum mechanical formalism. So what about the reference that Bohr makes to the association between measuring instruments and classical terms? The statement that "measuring instruments . . . serve to define, in classical terms, the conditions under which the phenomena appear" is about the material embodiment of classical concepts, one of the primary insights of Bohr's philosophy-physics, which is a condition for the possibility of objective description. That is, Bohr's emphasis is on the proper use of descriptive concepts. One must not confuse Bohr's insistence on the use of classical terms or concepts or descriptions with any such claim for the necessity for the application of the laws of classical physics, or with any such insistence on separate domains. Furthermore, as the foregoing example illustrates, *the* *distinction between "measured object" and "measuring agency" is not equivalent to that between microscopic and macroscopic.*[106] A more explicit statement of the fact that macroscopic systems can indeed be part of the "object" (requiring a quantum mechanical treatment) rather than the "instrument" can be found in Bohr's 1935 reply to Einstein, Podolsky, and Rosen in a discussion of the same example:

> The principal difference between the two experimental arrangements [i.e., the two-slit experiment with fixed and movable diaphragms] under consideration is, however, that in the arrangement suited for the control of the momentum of the first diaphragm [i.e., the arrangement with the movable diaphragm] *this body can no longer be used as measuring instrument* for the same purpose as in the previous case, *but must*, as regards its position relative to the rest of the apparatus, *be treated, like the particle traversing the slit, as an object of investigation*, in the sense that the quantum-mechanical uncertainty relations regarding its position and momentum must be taken explicitly into account. (Bohr 1998 [1935 essay], 77; italics in original)

While this example demonstrates that macroscopic entities can sometimes be part of the object of investigation, it is also the case that microscopic entities can sometimes be part of the agencies of observation, as illustrated, for example, by the case discussed in chapter 3 where the photon emitted from the flash of a camera is part of the measuring device rather than the object.

An important feature to be emphasized about the agential cut delineating object and instrument is that the particular role played by any particular part of the experimental arrangement—as part of the object or the instrument—is necessarily contingent on the details of the intra-action, since the experimental arrangement embodies the mutual exclusivity of the conditions for definability. For example, in the case of the movable diaphragm, since it is just the kind of device that is needed for defining "momentum," it serves as a good measurer of momentum and is thereby properly considered an instrument with respect to the measurement of momentum (and hence is properly given a classical description—see hereafter). On the other hand, a movable diaphragm is not what is required for a device to be able to define "position," that is, it is not a useful device for measuring position, and in fact we can expect the indeterminacy in the position to be so large that it will require quantum mechanical treatment, and indeed the movable diaphragm is an "object" with respect to the measurement of position.[107]

So while the passage just quoted cannot be understood as evidence for Bohr's alleged insistence on the existence of separate physical domains (as voiced by Rovelli and others), it does bring up some important points that deserve our attention: the highly contentious idea that classical concepts are required for the description of quantum phenomena. This is a serious issue, and I will investigate it in detail. I will then return to the other legitimate objections against the central role of the human and "piddling laboratory operations," as Mermin identifies them.

2b. Are classical concepts necessary for the description of quantum phenomena?

Bohr assigns a special or privileged role to classical concepts. According to Bohr, classical concepts are required for the description of all quantum phenomena.

> There must be quite definite and clear grounds, why you repeatedly declare that one must interpret observations classically, which lie absolutely in their essence. . . . It must belong to your deepest conviction and I cannot understand on what you base it. (Schrödinger to Bohr, October 13, 1935, quoted in Howard 1994)

This is perhaps the most contentious aspect of Bohr's philosophy-physics and the point at which many of even his most devoted colleagues part company with him. Note the contrast between this seeming terminological conservatism and the radical departure of Bohr's conceptual framework from classical ideas. Clearly Bohr is not conservative when it comes to challenging established ideas. But neither does his insistence on the necessity of the use of classical concepts, despite the inadequacy of the laws of classical physics, represent a stasis with respect to the descriptive vocabulary of physics. Nowhere does Bohr object to the introduction of nonclassical notions such as "isospin" or "positron" (a species of antiparticles that are not part of classical physics); nor would he have had any trouble with the introduction of the notion of "charm," or any other "flavor," or even "color" of quark had he lived long enough. What, then, is the nature and basis for this insistence on the use of classical concepts? And when precisely are they necessary?

Supporters, detractors, and critics of Bohr's views have suggested that this insistence (more than any other aspect of Bohr's philosophy-physics) is unjustified, and a result of an ideological commitment on Bohr's part. However, I will argue that what is at stake for Bohr is nothing less than the objectivity of science. If this is an ideological commitment, it is one that is at least shared by many scientists, philosophers of science, and members of the general public.[108]

Let's look more closely at what Bohr has to say about this issue. In his response to Einstein, Podolsky, and Rosen, Bohr makes the following explicit remarks concerning the necessary use of classical concepts:

> This necessity of discriminating in each experimental arrangement between those parts of the physical system considered which are to be treated as measuring instruments and those which constitute the objects under investigation may indeed be said to form a *principal distinction between classical and quantum-mechanical description of physical phenomena*. . . . While, however, in classical physics the distinction between object and measuring agencies does not entail any difference in the character of the *description* of the phenomena concerned, its fundamental importance in quantum theory, as we have seen, has its root in the indispensable use of classical *concepts* in the interpretation of all proper *measurements*, even though the classical *theories* [laws] do not suffice in accounting for the new types of regularities with which we are concerned in atomic physics. (Bohr 1998 [1935 essay], 81; italics in original)

So, first of all, Bohr starts out with the important point concerning the necessity in the interpretation of all proper measurements of discriminating *in each experimental arrangement* between those parts "which are to be treated as measuring instruments and those which constitute the object under investigation." In other words, what is at issue is the cut that makes a distinction between object and instrument. There is nothing inherent about this distinction—in fact, this is the whole point! Contrary to Einstein, Bohr does not assume a fixed, inherent separation between the instrument and object; rather, it is the materiality of the experimental arrangement, not some metaphysical preconception or an arbitrary choice on the part of the observer, that constitutes this distinction (see chapter 3).[109] Hence it would be incorrect to take the distinction between the instrument and the object to coincide with some (ill-defined) division between macroscopic and microscopic systems. In other words, since phenomena entail the inseparability of physical systems, which become distinguishable only as determinately bounded and propertied subsystems—object and instrument—through their intra-action, there is *no* justification for presuming that we can specify in advance or in all cases that what constitutes the instrument are all the macroscopic components and what constitutes the objects are all the microscopic components.

Now we can begin to approach the question of the necessity of classical concepts. Recall that Bohr argues that the inseparability of object and agen-

cies of observation is a consequence of the empirically derived "quantum postulate" in combination with his important insight that concepts are not ideations but specific material configurations (see chapter 3). Concepts are no more inherently meaningful (nor intra-linguistically semantically determinate) than are the boundaries and properties of entities inherently determinate. Rather, concepts become meaningful through their embodiment in the larger apparatus: that is, a physical concept is given definition by the specific materiality of the experimental arrangement. So, for example, Bohr tells us that "to measure the position of one of the particles can mean nothing else than to establish a correlation between its behavior and some instrument rigidly fixed to the support which defines the space frame of reference" (1935, 79). And if an experimental arrangement is suitable for defining "position" (e.g., fixed parts), then it is not suitable for defining the complementary variable, "momentum" (e.g., movable parts). Complementarity is a matter of material incompatibility: the instrument cannot have a part that is simultaneously both movable and fixed. *So the only well-defined (unambiguous) concepts that one has available are the particular concepts embodied in the specific experimental arrangement*. There are no others.

Now, since Bohr explicitly rejects the separability condition (of Einstein), he needs to secure objectivity by some other means. For Bohr, objectivity is not a matter of being at a remove from the object being observed, as predicated on the classical condition of externality, but a question of the unambiguous communication of the results of reproducible experiments. What makes the experiment reproducible and the description unambiguous? Once again it is the experimental arrangement's enactment of a cut through which the "instrument" and "object" obtain well-defined boundaries and properties, and particular embodied concepts obtain well-defined meanings, to the exclusion of others, that makes it possible to unambiguously account for the marks on bodies. In other words, *the terms that are unambiguously defined by the experimental arrangement are just the ones that we must use in the objective description of reproducible phenomena. This point goes directly to the fact that in Bohr's account, experimental arrangements are the material purveyors of semantic determination.*

This is the essence of Bohr's point about the necessity of what he calls "classical"—but perhaps should have called "embodied" or "contingently determinate"—concepts. Bohr does not ascribe a different physical nature to instruments but insists that to secure an objective description of the results of measurements, one must use a classical rather than quantum description, that is, a description based on concepts that are given meaning by the larger material arrangement. Bohr's point (in this case) is about the nature of description, not the nature of nature. His point is not that instruments are devices described by the laws of classical physics but that the term "classical" needs to be understood as a specification of those embodied terms that are conditioned by the cut and hence an epistemological subject-object distinction, which is not inherent but materially enacted. Being thus conditioned by a cut between "object" and "subject," such terms share the characteristic of terms in classical physics, which are predicated on an inherent subject-object distinction. Perhaps the difference in the nature of the cut—the fact that it is contingent in quantum mechanics and inherent in classical mechanics—should have been reason enough for Bohr to avoid using the term "classical" when what he was after was the descriptive terms (made) available (by the specific arrangement) for the unambiguous and reproducible (i.e., objective) accounting of phenomena.

In summary, Bohr's stake in the use of embodied concepts (the concepts that he unfortunately calls "classical") is to secure the possibilities for objectivity in the absence of an inherent distinction between subject and object or knower and known. Quantum physics is able to provide objective descriptions nonetheless because the apparatus enacts an agential cut between the object and the agencies of observation, as well as giving determinate meaning to those concepts embodied in the apparatus (to the exclusion of other complementary concepts). It is these embodied concepts (the only ones with determinate meanings) that must be used to provide an objective account of the phenomena.

So Bohr has legitimate reasons for insisting on the use of *embodied* ("classical") concepts. On the other hand, Bohr would have us pay a high price for salvaging objectivity from the wreckage of classical physics. In the absence of the ontological condition of separability in quantum physics, Bohr secures objectivity on epistemological grounds, thus cementing epistemological concerns into the base of the theory. In one breath, Bohr insists that "humans" be understood as "parts of nature," and in a second breath he privileges "humans" as special envoys sent out to secure the grounds for objectivity.

Having thus separated out objections based on misunderstandings from legitimate concerns, I can summarize some of the remaining challenges that Bohr's formulation faces: (1) in the absence of the ontological condition of separability in quantum physics, Bohr secures objectivity on purely epistemological grounds; (2) in Bohr's account, physics only tells us about human-based (laboratory) practices, not the nature of nature; and (3) Bohr interprets quantum theory as being solely about the outcome of laboratory measurements. Additionally, it is important to understand how the measurement question is resolved. The point is that measurements are physical processes, and therefore an account of measurements should emerge from, rather than be imposed on, the theory.

In what follows, I consider the possibility of moving Bohr's formulation beyond these objectionable humanist remnants. Some of the questions that will need to be addressed in a viable posthumanist elaboration include: Is it possible to secure objectivity on ontological, rather than merely epistemological, grounds? Is it possible to honor Bohr's profound insights concerning the relationship between concepts and physical arrangements without inserting the human into the foundations of the theory? Is it possible to understand this fundamental relationship ontologically and to understand the theory as saying something meaningful about the physical world and not merely about laboratory exercises or other human contrivances?

AN AGENTIAL REALIST INTERPRETATION OF QUANTUM MECHANICS

> Against the sometimes maddening frustration brought about by a study of these ponderous essays [Bohr's, of course] is the indisputable fact that nobody has succeeded in saying anything manifestly better in the sixty years since Bohr started talking about complementarity. How he could have known that they would fail, right from the start, is yet another puzzle. As a philosopher Bohr was either one of the great visionary figures of all time, or merely the only person courageous enough to confront head on, whether or not successfully, the most imponderable mystery we have yet unearthed.
>
> —N. DAVID MERMIN, *Boojums All the Way*

Bohr is not alone in assigning the observer and questions about epistemology a privileged role in quantum theory. Indeed, some interpretations go much further than Bohr and take mind or consciousness to be a primary and ineliminable ingredient. For example, it has been proposed that the mind is responsible for the collapse of the wave function. Such accounts are deeply humanistic in their foundations, echoing the pre-Copernican stance that would place the human at the center of all that is.

In this section I propose a posthumanist elaboration of Bohr's account of quantum physics. Posthumanism, in my account, can be understood as a thoroughgoing critical naturalism, an approach that understands humans as part of nature and practices of knowing as natural processes of engagement with and as part of the world. In particular, the acknowledgment that humans are part of nature entails the simultaneous recognition that our understanding of nature as that which is disclosed through scientific practices entails an appreciation of the fact that scientific practices are natural processes rather than external impositions on the natural world.[110] Such a naturalist understanding would be grounded in our best scientific theories rather than in philosophical preconceptions and would have us conceive of science as a natural activity conducted within or by nature, not an investigation of nature from the outside. A commitment to understanding humans as a part of nature and to understanding scientific practices as natural processes—in particular, causal intra-actions—is a basic tenet of Bohr's approach. In a sense, what is needed is to push Bohr toward a more thoroughgoing naturalism.

I have proposed agential realism as an explication and further elaboration of Bohr's philosophy-physics. In particular, agential realism makes explicit important ontological dimensions of Bohr's epistemological framework and extends it in directions required for the logical consistency of the framework, challenging anthropocentric elements of Bohr's approach and extending Bohr's insights beyond laboratory exercises and questions of human knowledge production (see chapters 3 and 4). In this section, I consider how these agential realist elaborations contribute to placing Bohr's insights on a firmer ground with respect to interpretative questions. That is, I consider the possibility that the agential realist account provides the basis for a more coherent and robust interpretation of quantum theory. The interpretative insights of the agential realist elaboration of Bohr's philosophy-physics are considered in light of the new experimental and theoretical insights discussed in previous sections.

1 AGENTIAL REALISM: UNDERSTANDING PHENOMENA ONTOLOGICALLY, OR A RELATIONAL BOHRIAN ONTOLOGY

> Why should physics be able to produce more than a description of the world in the world's own terms, by relating some parts of the world to other parts? . . . Correlations have physical reality; that which they correlate does not.
>
> —N. DAVID MERMIN,
> "What Is Quantum Mechanics Trying to Tell Us?"

Among the competing interpretations of quantum mechanics are several different interpretations based on relational ontologies.[111] The Ithaca Interpretation of Quantum Mechanics (IIQM) (Mermin 1998) and the Relational

Quantum Mechanics account (Rovelli 1996; Smolin 2001) have important features in common with each other and with the view presented here.[112] Relational ontologies have also been discussed by Paul Teller (1986, 1989), Don Howard (1989), and Arthur Fine (1989).

The main feature shared by these approaches is the rejection of "particularism" (Teller 1989). In essence, particularism is the view that the world is composed of individuals and that each individual has its own roster of nonrelational properties.[113] (This is what I have previously referred to as a metaphysical individualism.) Teller awakens us to the fact that "we tend unreflectively to presuppose particularism as a facet of our conception of the world, a facet which never gets explicitly stated and yet conditions all our thinking" (213). As we have seen, there is reason to be suspicious of particularism on both theoretical and empirical grounds. Bohr directly challenged the particularist view with great passion, remarkable insight, and incomparable ingenuity, if not always with the utmost eloquence.

In chapters 3 and 4, I clarified important elements of Bohr's account, made explicit implicit ontological dimensions of Bohr's epistemological framework, proposed an understanding of phenomena that is no longer restricted to the results of laboratory exercises, and elaborated his insights in a posthumanist direction that decenters the human. Importantly, I suggest that Bohr's notion of a phenomenon be understood ontologically. In particular, I take the primary ontological unit to be *phenomena*, rather than independent objects with inherent boundaries and properties. In my agential realist elaboration, phenomena do not merely mark the epistemological inseparability of "observer" and "observed"; rather, *phenomena are the ontological inseparability of intra-acting "agencies."* That is, *phenomena are ontological entanglements*. Significantly, in my account, phenomena are not mere laboratory contrivances. Phenomena are the basis for a new ontology. Phenomena are what are observed in laboratories, but they are more than that: they are the basic units of existence.[114]

Phenomena are ontologically primitive relations—relations without preexisting relata.[115] On the basis of the notion of *intra-action*, which represents a profound conceptual shift in our traditional understanding of causality, I argue that it is through specific agential intra-actions that the boundaries and properties of the "components" of phenomena become determinate and that particular material articulations of the world become meaningful.[116] A specific intra-action (involving a specific material configuration of the "apparatus") enacts an *agential cut* (in contrast to the Cartesian cut—an inherent distinction—between subject and object), effecting a separation between "subject" and "object." That is, the agential cut enacts a resolution *within* the phenomenon of the inherent ontological (and semantic) indeterminacy. In other words, relata do not preexist relations; rather, relata-within-phenomena emerge through specific intra-actions.

In performing this elaboration, I honor Bohr's crucial insight about the materiality of concepts while moving away from his anthropocentric reliance on human-based theoretical concepts as embodied by static prefabricated laboratory instruments. In particular, I propose a crucial shift in understanding the nature of apparatuses: apparatuses are to be understood not as mere laboratory instruments, static instrumental embodiments of human concepts, but as open-ended and dynamic material-discursive practices, through which specific "concepts" and "things" are articulated. Not only does this shift provide a much more dynamic and realistic conception of laboratory endeavors, but it removes altogether the restriction to human-based practices and offers a new understanding of discursive practices that rescues them from their current humanist incarnations. That is, in wresting Bohr's formulation away from some of its most persistent humanist elements, the question arises as to how to understand Bohr's key insight concerning the role of human concepts in scientific practices. Bohr had his eye only on laboratory measurements. He was unconcerned about the larger ontological implications: about what quantum mechanics tells us about the nature of existence. But if this is precisely what we want to consider, then we have to rework Bohr's crucial insights, providing a posthumanist understanding that does not fix the human (human concepts, human practices, human knowledge) at the foundations of the theory. (My agential realist elaboration follows through on Bohr's insights in a way that is more consistent with the logic of his argument than his own formulation.) In chapter 4, I offer a lengthy exposition of these issues, which I will not repeat here. Instead I will summarize some key points.

Fortunately, Bohr gives us some robust tools to work with. As I have argued, Bohr's point that apparatuses are productive of the phenomena they measure is not to be understood as some idealist claim that reality is a product of human concepts. On the contrary, Bohr insists that the reason why theoretical concepts matter to the results produced is that concepts are specific material arrangements. The shift that I propose from linguistic concepts to discursive practices (which are specific material practices) places the emphasis on the dynamics of material practices (including scientific ones) while building on this important Bohrian insight in a way that frees it from its anthropocentric moorings.

First of all, it is important to recognize that apparatuses are not merely human-constructed laboratory instruments that tell us how the world is in accordance with our human-based conceptions. Rather, apparatuses are specific material configurations (dynamic reconfigurings) of the world that play a role in the production of phenomena. The fact that apparatuses are productive of phenomena, that they contribute to, and are part of, the phenomena they produce, is not about a mysterious and unexplained linkage between human concepts and the physical phenomena produced in experiments. What is at issue is that specific material practices, that is, specific dynamic material configurings of the world, *causally* produce specific material phenomena, as part of the ongoing differential performance of the world. Phenomena are not the mere result of human laboratory contrivances or human concepts. Phenomena are specific material performances of the world.

In other words, apparatuses are specific material-discursive practices. Discursive practices are not speech acts. Rather, discursive practices are specific material configurings of the world through which determinations of boundaries, properties, and meanings are differentially enacted. It is this enactment of ontic-semantic determinacy that is at the core of what discursivity entails. To assume that meaning is a property of individual words or groups of words is to stay within a linguistic frame of meaning making. Discourse is not a synonym for language. Discursive practices are the material conditions for making meaning. In my posthumanist account, meaning is not a human-based notion; rather, meaning is an ongoing performance of the world in its differential intelligibility. Intelligibility is usually framed as a matter of intellection and therefore a specifically human capacity. But in my agential realist account, intelligibility is a matter of differential responsiveness, as performatively articulated and accountable, to what matters. Intelligibility is not an inherent characteristic of humans but a feature of the world in its differential becoming. The world articulates itself differently.

That is, discursive practices are ongoing agential intra-actions of the world through which determinacy is enacted within the phenomena produced. Discursive practices are causal intra-actions—they enact causal structures through which one "component" (the "effect") of the phenomenon is marked by another "component" (the "cause") in their differential articulation. In its causal intra-activity, "part" of the world becomes determinately bounded and propertied in its emergent intelligibility to another "part" of the world. Discursive practices are boundary-making practices that have no finality in the ongoing dynamics of agential intra-activity. Hence, to the extent that human concepts have a role to play, they do so as part of the material configuration of the world. Reality does not depend on the prior existence of human beings; rather, the point is to understand that "humans" are themselves natural phenomena.

Importantly, materiality is also reconceptualized in terms of the shift in ontology from things to phenomena. In an agential realist account, matter does not refer to a fixed substance; rather, *matter* is substance in its intra-active becoming—not a thing but a doing, a congealing of agency. Matter is a stabilizing and destabilizing process of iterative intra-activity. Phenomena—the smallest material units (relational "atoms")—come to matter through this process of ongoing intra-activity. Materiality and discursivity are mutually implicated in the dynamics of intra-activity. This is an outgrowth of the agential realist reconceptualizations of causality and agency.

The world is made up of phenomena. Scientific practices are specific forms of engagement that make specific phenomena manifest. What I am proposing is, after all, a realist interpretation. The implications of agential realism for understanding the nature of scientific practices are further explored in chapter 8. In the remaining sections of this chapter, I consider the specifics of removing the anthropocentric elements of Bohr's account and consider the possibility of resolving the remaining challenges to his account using my agential realist elaboration.

2 BEYOND PIDDLING LABORATORY MEASUREMENTS

> To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise. A serious formulation will not exclude the big world outside the laboratory.
>
> —N. DAVID MERMIN, "What Is Quantum Mechanics Trying to Tell Us?"

Some interpretations of quantum mechanics place substantial demands on the nature of the measuring instrument. In his 1935 paper, Schrödinger asserts that the disentanglement of object and instrument requires "the living subject actually taking cognizance of the result of the measurement" (Schrödinger 1935, 162). Sentience, consciousness, and intelligence have all been suggested as necessary components of the measuring device. Significant inanimate requirements have also been imposed, including the presence of a gravitational field (Penrose 1989) and thermodynamic irreversibility. In this light, Bohr's requirement that the measuring device be macroscopic seems rather minimal, even banal.

To Bohr's way of thinking, the macroscopic nature of the larger experimental arrangement is never in question. Since his sole concern was the proper objective description and interpretation of laboratory measurements, the device simply is macroscopic: the fact of the matter is that humans do not possess a perceptual apparatus that can directly detect atomic events, and we therefore depend on pointers and other macroscopic devices to help us discern the results of experiments. Bohr was not in the business of doing philosophy for philosophy's sake; for Bohr, the physics guided and motivated the philosophy, not the other way around. As a physicist, Bohr's primary concern was the understanding of experimental outcomes. The question of whether or not his notion of phenomena has any generality beyond measurement intra-actions that take place in the laboratory, for example, did not seem to be anywhere on his radar screen.

Agential realism provides a framework for thinking through the larger implications of the theory, beyond what physics tells us about "piddling laboratory operations." Taking the ontological implications seriously, agential realism also reworks our understanding of what happens in the laboratory. Let's examine what this elaboration means for the notion of measurement.

What is a measurement? Is it an irreducibly human-centered notion? What is involved in the "unambiguous comparison of some property of the object under investigation with a corresponding property of another system, serving as a measuring instrument"? As we have seen, the mere collision of two particles does not constitute a measurement. Rather, for one system to have properly measured some property of another system requires a correlation of the properties of the two systems. But we cannot be talking about the correlation of the inherent properties of two separately determined systems, as one assumes from a classical worldview, because intra-acting systems are entangled and do not have separately determinate boundaries and properties. The boundaries and properties of component parts of the phenomenon become determinate only in the enactment of an agential cut delineating the "measured object" from the "measuring agent." This cut, which enacts a causal structure that entails the "causal agent" ("measured object") marking the "measuring agent," is determined by the specific experimental arrangement, or material configuration. So a correlation between the "causal agency" ("cause") and "measuring agency" ("effect") is marked by the intra-action of one part of the phenomenon with another.

Measurements, then, are causal intra-actions, physical processes. What we usually call a "measurement" is a correlation or entanglement between component parts of a phenomenon, between the "measured object" and the "measuring device," where the measuring device is explicitly taken to be macroscopic so that we can read the pattern of marks that the measured object leaves on it. But, as discussed earlier, Bohr does not ascribe special ontological status to macroscopic measuring instruments: there are not two separate domains of nature, one macroscopic and one microscopic. Bohr's point, rather, in his emphasis on macroscopic devices is a point about the unambiguous definition and communication of materially embodied concepts. But in my posthumanist elaboration, human concepts or experimental practices are not foundational to the nature of phenomena. Phenomena are not the result of an external imposition of human-based conceptual schemata. Rather, phenomena are the manifestation of material-discursive practices, where discursive practices are not placeholders for human concepts but specific material articulations of the world. With this elaboration in mind, it doesn't make sense to hold onto an anthropocentric conception of measurement; on the contrary, a commitment to a thoroughgoing naturalism suggests that we understand measurements as causal intra-actions (some of which involve humans).

Another way to put this is that if a *measurement is the intra-active marking of one part of a phenomenon by another*, where phenomena are specific ontological entanglements, that is, specific material configurations of the world, then there is nothing inherent in the nature of a measurement that makes it irreducibly human centered. We need not reserve the notion of "measurement" for intra-actions that we humans find useful in laboratory practices, but can understand it more generally.[117] Phenomena are not mere human contrivances manufactured in laboratories. Phenomena are constitutive of reality. Parts of the world are always intra-acting with other parts of the world, and it is through specific intra-actions that a differential sense of being—with boundaries, properties, cause, and effect—is enacted in the ongoing ebb and flow of agency. There are no preexisting, separately determinate entities called "humans" that are either detached spectators or necessary components of all intra-actions. Rather, to the extent that "humans" emerge as having a role to play in the constitution of specific phenomena, they do so as part of the larger material configuration, or rather the ongoing reconfiguring, of the world. Thus no a priori privileged status is given to the human—and this is precisely the point. "Humans" are emergent phenomena like all other physical systems.

Where does this leave the notion of objectivity, which Bohr explicitly hinges on a community of human observers?

3 BEYOND AN EPISTEMOLOGICAL CONCEPTION OF OBJECTIVITY

In the previous section, I discussed the fact that Einstein maintained a belief in separability as the very condition for the possibility of objectivity. That is, in Einstein's view, if the condition of separability is denied, then objectivity is no longer possible. Bohr disagreed with Einstein's stance. Bohr argued that it is possible to secure the notion of objectivity in the face of quantum nonseparability because objectivity is not predicated on an inherent or Cartesian cut between observer and observed, but rather what is required for objectivity is an unambiguous and reproducible account of marks on bodies. This is made possible by the intra-active enactment of a "cut" (determined by the larger experimental arrangement) that unambiguously differentiates the "object" (that which "causes" the mark) from the "agencies of observation" (the "effect" or that which receives the mark), thereby constituting a reproducible and unambiguous measurement of one part of the phenomenon (the object) by another part (the agencies of observation).

What Bohr and Einstein share in their very different conceptions of the role of the human observer, which occupies a special position in both accounts, is the humanist belief in the existence of individual humans that are separately determinate from the physical interactions being investigated. By contrast, I am interested in a posthumanist understanding that does not presume the human to be a special system separate from the natural processes that he or she observes, but rather one that seeks to understand the emergence of the "human" along with all other physical systems. To exclude the human from the realm of nature and sequester him or her in the realm of culture is not only to install the nature-culture divide in the foundations of the theory but to forgo the possibility of understanding how this boundary gets drawn.

In my agential realist elaboration of Bohr's framework, objectivity can be given an ontological formulation that honors the insights of both Bohr and Einstein while rejecting the humanist or anthropocentric elements of each. In particular, it is possible to replace Bohr's epistemological formulation of objectivity with an ontological formulation. This stronger formulation of objectivity is possible in my agential realist account because phenomena are explicitly ontological in nature, not merely epistemological. It is through specific agential intra-actions that the boundaries and properties of the causally related components of phenomena become ontologically determinate and that particular concepts become meaningful (that is, semantically determinate). Intra-actions enact *agential separability*—the condition of exteriority-within-phenomena. Separability is not inherent or absolute, but intra-actively enacted relative to a specific phenomenon. The notion of agential separability strengthens Bohr's notion of objectivity from the intersubjective human-based criteria of reproducible and unambiguous communication to a more general ontological criterion, founded, like Einstein's notion of objectivity, on a condition of separability. Agential separability, however, is not rooted in a metaphysical insistence on the absolute nature of separability, but rather as it is disclosed by empirical findings that reveal its contingent nature.

In summary, "measurements" are causal intra-actions. They are not mere laboratory contrivances that depend on human beings for their configuration and operation. They are not the artifacts of special agents that are not accounted for by the theory. "Observer" and "observed" are nothing more than two physical systems intra-acting in the marking of the "effect" by the "cause"; no human observers are required (though "humans" may emerge as being part of practices). And objectivity is not defined in reference to a human observer: it is not merely about what humans can do to facilitate unambiguous communication about laboratory results. Rather, objectivity is a matter of accountability to marks on bodies. Objectivity is based not on an inherent ontological separability, a relation of absolute exteriority, as Einstein would have it, but on an intra-actively enacted agential separability, a relation of exteriority within phenomena. The reproducibility and unambiguous communication of laboratory results are possible because the agential cut enacts determinate boundaries, properties, and meanings, as well as a causal structure in the marking of the "measuring agencies" ("effect") by the "measured object" ("cause") within the phenomenon. Accountability to marks on bodies requires an accounting of the apparatuses that enact determinate causal structures, boundaries, properties, and meanings. Crucially, the objective referent of measured values is phenomena, not (some abstract notion of) objects (which do have an independent existence).[118] Objectivity, then, is about being accountable and responsible to what is real.

4 BEYOND QUESTIONS OF HUMAN KNOWLEDGE

> Why presume in advance that the bounds of the human organism are ultimately the boundaries of the scientific measuring system . . . rather than insisting that those boundaries should be specified from within scientific practices or measurement interactions themselves?
>
> —JOSEPH ROUSE, *How Scientific Practices Matter*

Bohr's focus was on epistemology, questions of the nature of human knowledge. I believe that this was due to what he saw as being at stake in the proper interpretation of quantum mechanics. If Einstein's primary commitment was separability for the sake of objectivity, Bohr's was objectivity in the absence of inherent separability. According to Bohr, the experimental evidence forced on us a recognition of quantum nonseparability. Given this fact, the task remained to understand the conditions for possibility of the objective description of quantum phenomena. This was no trivial task, and in his dogged determination to work out the details and convince his colleagues of how complementarity makes this possible, he focused on the questions of human knowledge. This singular focus did not help Bohr make his case. On the contrary, it can be argued that Einstein and others would have found Bohr's account more compelling if he had more thoroughly developed the ontological implications of his insights. For clearly what is at issue in the shift from classical to quantum physics is not merely the nature of human knowledge but also the nature of being. In this section, I will argue that following Bohr's insight that quantum physics makes it necessary to understand humans as part of nature to be understood suggests a radical reconception of the notion of knowing, beyond what Bohr proposes, and that this understanding helps to further clarify crucial ontological questions that Bohr left unanswered.

Bohr moves toward a posthumanist formulation in his insistence that we understand ourselves as part of nature. But then he falls back into the seductive arms of humanism when he talks about the humanist subject that stands fully formed before the action and chooses a particular apparatus as part of doing an experiment. But as we saw, the particular configuration that an apparatus takes is not an arbitrary construction of "our" choosing; nor is it the result of forces such as power or culture or history impressing themselves on scientific practices and determining the outcome. "Humans" do not simply assemble different apparatuses for satisfying particular knowledge projects; rather, "humans" are themselves specific parts of the world's ongoing reconfiguring. To the degree that laboratory manipulations, observational interventions, concepts, and other human practices have a role to play, they do so as part of the material configuration of the world in its intra-active becoming. "Humans" are part of the world-body space in its dynamic structuration.

Hence, in contrast to the spectator theory of knowledge, what is at issue is not knowledge *of* the world from above or outside, but *knowing as part of being*. Indeed, the agential realist formulation brings to the fore questions of the ontology of knowing. In traditional approaches to epistemology, the knowing subject is a conscious self-aware self-contained independent rational agent that comes to a knowledge project fully formed. But if knowing is to be understood naturalistically, that is, in terms of our best scientific theories, then it should be clear at this point that the relationship between the knower and the known does not follow the traditional philosophical model. The knower cannot be assumed to be a self-contained rational human subject. Rather, subjects (like objects) are differentially constituted through specific intra-actions. The subjects so constituted may range across some of the traditional boundaries (such as those between humans and nonhumans and between self and other) that get taken for granted (see chapter 8 for a more in depth discussion). Knowing is a distributed practice that includes the larger material arrangement. To the extent that humans participate in scientific or other practices of knowing, they do so as part of the larger material configuration of the world and its ongoing open-ended articulation.

Knowing is not an ideational affair, or a capacity that is the exclusive birthright of the human. Knowing is a material practice, a specific engagement of the world where part of the world becomes differentially intelligible to another part of the world in its differential accountability to or for that of which it is a part.

Hence, knowing is not a play of ideas within the mind of a Cartesian subject that stands outside the physical world the subject seeks to know. In my naturalistic conception, knowing is a physical practice of engagement, and as with other physical processes, there should be an account of it within our scientific theory. Bohr's impulse to understand scientific practices as a part of what it is that science understands is right on the mark. He just doesn't follow through on it.

5 ON THE PROBLEM OF MEASUREMENT

> In the first place, we must recognize that a measurement can mean nothing else than the unambiguous comparison of some property of the object under investigation with a corresponding property of another system, serving as a measuring instrument, and for which this property is directly determinable according to its definition in everyday language or in the terminology of classical physics.
>
> —BOHR, *The Philosophical Writings of Niels Bohr*

Although the question of measurement is central to Bohr's understanding of quantum physics, he does not directly discuss the so-called measurement problem. Perhaps the closest he comes to saying anything that might be seen as remotely or implicitly engaging this issue, which has become a focal point of discussions in the foundations of quantum mechanics, is the following:

> In the system to which the quantum mechanical formalism is applied, it is of course possible to include any intermediate auxiliary agency employed in the measuring processes. Since, however, all those properties of such agencies which, according to the aim of the measurement, have to be compared with corresponding properties of the object, must be described on classical lines, their quantum mechanical treatment will for this purpose be essentially equivalent with a classical description. The question of eventually including such agencies within the system under investigation is thus purely a matter of practical convenience, just as in classical physical measurements; and such displacements of the section [i.e., cut] between object and measuring instruments can therefore never involve any arbitrariness in the description of a phenomenon and its quantum mechanical treatment. *The only significant point is that in each case some ultimate measuring instruments*, like the scales and clocks which determine the frame of space-time coordination—on which, in the last resort, even the definitions of momentum and energy quantities rest—*must always be described entirely on classical lines, and consequently kept outside the system subject to quantum mechanical treatment.* (Bohr 1998 [1938 essay], 104; italics mine)

As this passage shows, from Bohr's perspective there is no problem. There is no indication that measurements entail any kind of physical collapse, only cuts. What is at issue when it comes to measurements is just the set of concerns we've been discussing: unambiguous (objective) descriptions of quantum phenomena and the role of the (agential) cut in delineating "object" from "measuring instrument" (within a phenomenon).[119] But alas, these points do not seem to address the question that is most pertinent to those who insist that there is a measurement problem: how is it possible to account for the fact that the measurement of any quantity produces a determinate value even though the quantum formalism permits states with indeterminate values? What is it about the nature of the correlation between "object" and "observing instrument" such that a superposition of states reduces to a single determinate value for the quantity in question?

Let's start by examining the nature of the correlation that measurements entail. According to Bohr, "to measure the position of one of the particles can mean nothing else than to establish a correlation between its behavior and some instrument rigidly fixed to the support which defines the space frame of reference" (Bohr 1998 [1935 essay], 79). It is possible, on the basis of my agential realist elaboration of Bohr's framework and new experimental evidence, to be more explicit than Bohr about the nature of measurement correlations. Recall that Schrödinger introduces the notion of an entanglement between the object and the measuring system in order to try to understand the "collapse." However, Schrödinger understands the notion of entanglements in an epistemic sense: the shift in the wave function of the object is due to the entanglement of our *knowledge* of the "object" with our *knowledge* of the "measuring instrument." Schrödinger then invokes the cognizing agent, a conscious subject, as the vehicle for the reduction of the wave function. By contrast, I have argued that it is appropriate to understand Bohr's notion of a phenomenon as an *ontological entanglement* of agentially intra-acting "components." In what follows, I will argue that this important elaboration resolves the difficulty without the need for a supplementary agent, like consciousness.

At first glance, ontologizing the notion of entanglement seems to make matters worse. At least on Schrödinger's epistemic interpretation of entanglements he can argue that the collapse is not a physical occurrence but rather simply a reduction in our ignorance: that is, once we perform the measurement we no longer have an entire probability distribution of potential values to keep track of since the measurement process picks out just one value among the set of potential values. That is, our ignorance is resolved by finding the result. But how can we account for the fact that measurements produce determinate values if we understand entanglements ontologically?

In my discussion of recent experiments that address key foundational issues I presented evidence to support the idea that phenomena are ontological entanglements (see especially the realization of which-path experiments, most notably the quantum eraser experiments). In their analysis of the quantum eraser experiment, Scully et al., for example, show that the entanglement of the object and the measuring apparatus accounts for the fact that an interference pattern results from the erasure of which-path information. Indeed, the fact that the interference pattern is "restored" (actually a new one appears that is an extension of the previous one—now the photodetector is also entangled) when the which-slit information is erased indicates that the quantum coherence was not destroyed by the which-slit measurement, that is, the wave function superposition was not physically collapsed into a mixture. In fact, Scully et al. explain that *the entanglement* even accounts for the very fact that the which-slit detection "*destroys*" the interference pattern.[120] That is, the wave function is not collapsed in the sense of physically destroying the superposition or entanglement so much as establishing or extending it in such a way as to account for the observed phenomenon. Hence, what we find is that there is an important sense in which measurements create and further extend entanglements (since measurements produce correlations between "instruments" and "objects"). But how can we then explain the resolution of the ontological indeterminacy (as symbolized

by a superposition) through measurement interactions? This paradox—whether ontological indeterminacy is resolved or extended through measurement intra-actions—goes to the core of the measurement problem.

In an agential realist account, the resolution of ontological indeterminacy is understood in terms of the enactment of agential separability. Recall that boundaries and properties are only determinate *within* a given phenomenon through the enactment of an agential cut. The agential cut is determined by the materiality of the larger experimental arrangement, which delineates "measured object" from "measuring agency," while providing the material conditions of possibility for particular concepts to be meaningful at the exclusion of others. The body of the "measuring instrument" is marked in its correlation with the particular agentially determinate property of the "measured object." This *agential separability* is an unambiguous resolution of the ontological indeterminacy *within* the phenomenon. And this is precisely the insight we need to resolve the paradox.

Suppose we could "peek" inside a phenomenon. What would we see? If we were to peek inside the phenomenon, we would find that the mark the "object" makes indicates a specific definite value of the property being measured. In other words, the "measuring instrument" (inside or rather as part of the phenomenon) would indicate a definite value corresponding to one eigenvalue or another (e.g., there would be a pointer pointing in a specific direction). But *this is precisely what we do when we perform a measurement—we are "peeking" inside a phenomenon.* We don't have an "outside" view of the phenomenon itself, which is what is needed to observe the entanglement. To get such an outside view, we'd have to enlist a further auxiliary apparatus that can be used to measure the "original" phenomenon in question. Of course, such an attempt entails the further entanglement of the new auxiliary apparatus and the "original" phenomenon, constituting a new phenomenon. By some clever design we may in fact by this method be able to detect the entanglement (as in the ingenious quantum eraser experiments), but we still never see pointers indicating indeterminate values, since *with every measurement we are "looking inside a phenomenon,"* only now the phenomenon in question is the new extended one.

There is no "collapse"—no additional physical mechanism (beyond that governed by the quantum theory)—that transforms a superposition or entanglement that exists before the measurement into a definite state upon measurement. Rather, *what is at issue is the proper accounting of agential cuts within the specific phenomenon in question.* The key point is that *agential separability is enacted only within a particular phenomenon.* This point also goes to the heart of the issue of objectivity: in the absence of an inherent separability, *objectivity is secured through agential separability*. There are not separately determinate entities with inherently determinate properties, as Einstein would have us believe; nonetheless there are determinate marks on bodies produced through specific intra-actions. There is no absolute condition of exteriority to secure objectivity, but this doesn't mean that objectivity is lost. Rather, objectivity is a matter of exteriority-within-the-phenomenon.

The paradox is thus explained on the basis of entanglements and agential separability, without any need for a physical collapse mechanism. I will now give a more detailed explication of the crucial points while making contact with Bohr's account of measurement in the passage quoted earlier.

In Bohr's account, all systems evolve according to the SE, that is, the laws of quantum mechanics—period. So what does he mean by a "classical description"? His insistence that classical descriptions are necessary to objectively (unambiguously) describe the outcome of a measurement is clearly not an injunction to use the laws of Newtonian physics. What is at issue is a directive to use a *description* that is appropriate for separately determinate systems (as classical physics assumes). Separable systems can properly be described as mixtures. Recall that a mixture is a combination of individual states with separately determinate values of the property in question. Unlike the situation of an entangled state, a mixture can be expressed as the product of separate individual states: what is the case for system S (as separately determinate from system A) times what is the case for system A (as separately determinate from system S), where, for example, A represents the apparatus, and S represents the system of interest. In the account offered here, measurements do not produce absolutely separate states, in the sense of a relation of absolute externality; rather, the states are agentially separated *within* the phenomenon.[121] What Bohr is essentially saying is that within a phenomenon, where we have agential separability, the mark on the "measuring instrument" (e.g., the direction of a pointer) is *describable* as a mixture (even though it is *not* strictly speaking a mixture). That is, it appears as a mixture if the degrees of freedom of the instruments are bracketed, which is just what is done in describing the instrument classically. Indeed, it is in this sense that a "classical description" is given. If, however, we are talking about a property that is not made determinate by the particular experimental arrangement in use (e.g., a complementary property), then we must use a quantum mechanical treatment—meaning that we must take the indeterminacy into account: that is, it is not possible to describe it as a mixture.[122] Now, as Bohr tells us, we are free to reposition the agential cut by using some further auxiliary apparatus such that the "measuring agencies" are now included as part of the system under investigation. This constitutes the formation of some new phenomenon, and everything works in the usual way (except now, of course, the "original" measuring agencies no longer serve this purpose). Bohr tells us that "the only significant point is that in each case [no matter where the agential cut is made] some ultimate measuring instruments . . . must always be *described* entirely on classical lines, *and consequently kept outside the system subject to quantum mechanical treatment*." That is, agential separability is enacted in measurement intra-actions and it is precisely what is required for the possibility of an objective account. Hence, as I mentioned earlier, for Bohr there is no measurement problem; in his account, the issue is addressed precisely by the difference between describing "mixtures" classically and superpositions quantum mechanically.

Bohr's argument (in my elaboration) is completely in line with the result obtained by Asher Peres (1974) in a beautiful little paper entitled "Quantum Measurements Are Reversible," published over a quarter century ago.[123] Using a simple and elegant analysis, Peres finds that "the state of the measured system alone, which was pure before its interaction with the instrument, appears as a mixture as a consequence of the measurement, if the degrees of freedom of the instrument are ignored" (886–87). But "ignoring the instrument" is precisely what Bohr has in mind when he says that the measuring instrument, described entirely on classical lines, is kept outside the system subject to quantum mechanical treatment. "The state of the complete system (including the instrument) is always pure," writes Peres (886). The measurement process is indeed described by a "continuous unitary transformation of the states vector of the observed system and the apparatus"; there is no "collapse" involved (886).

The crucial point is agential separability. It matters whether or not we are "looking" inside the phenomenon (in which case the "instrument" itself is excluded from the description, and it is only the marks on the "instrument," indicating and correlated with the values intra-actively attributable to the "object"-in-the-phenomenon as described by a mixture, that are being taken account of), or viewing that particular phenomenon from the "outside" (via its entanglement with a further apparatus, producing a new phenomenon, in which case the "inside" phenomenon as "object," including the previously defined "instrument," is treated quantum mechanically). The point is the same as one I raised earlier: a "measuring instrument" cannot characterize (i.e., be used to measure) itself.[124] What is at issue is simply the fact that "measuring agencies" cannot take themselves into account (the role of "measuring agency" is complementary to the role of "measured object"), and hence they can't measure their own entanglement with the measured object. That is, it is important to realize that although the full quantum behavior of the entire phenomenon cannot be made explicit given this particular measurement because the "instrument" cannot be used to characterize itself, we should not conclude from the fact that the entanglement is not made explicit by this measurement that the entanglement has become ontologically "disentangled." *The agential cut does not disentangle the phenomenon into independent subsystems*; after all, it is their very intra-action (their nonseparability) that makes manifest particular marks on bodies in the first place. That is, the agential cut, because of the "local" determinacy it enacts, provides for the registering of a determinate value of the property question, and hence enables a description in terms of mixtures, without destroying the entanglement. *What the agential cut does provide is a contingent resolution of the ontological inseparability within the phenomenon* and hence the conditions for objective description: that is, it enables an unambiguous account of marks on bodies, but only within the particular phenomenon. Strictly speaking, *there is only a single entity*—the phenomenon—and hence the proper objective referent for descriptive terms is the phenomenon.

In other words, what is at issue is the fact that we are either describing a mark on the "measuring agency" (e.g., a pointer pointing in a definite direction), in which case what it measures is its correlation with the system with which it intra-acts, constituting a particular phenomenon; or we make a different placement of the agential cut, using a different experimental arrangement such that the complete "original" phenomenon, this time including what was previously marked as the "measuring agency," is being measured by the "new" "measuring agency," in which case it is possible to characterize the existing entanglement. *It's all a matter of where we place the cut. The solution to the "measurement problem" is recognizing that what is at stake is accountability to marks on bodies in their specificity by attending to how different cuts produce differences that matter.*

My agential realist resolution of the measurement problem is consistent with the recent experimental realizations of quantum erasers, and I end this section with a few comments in this regard. Recall that the erasure of which-path information has been shown to result in the reappearance of an interference pattern signaling the extant quantum behavior, which had otherwise looked as if it had been destroyed when the which-path detector made the paths distinguishable and the interference pattern seemed lost forever. As Greenstein and Zajonc (1997) point out, it is not trivial to detect the extant quantum behavior in quantum eraser experiments. The experimenters must

be clever enough to design an experiment that can detect the entanglement (e.g., the success of the quantum eraser experiment of the Rochester group depended on the observation of the appropriate coincidence counts between two detectors): "Quantum behavior will not be seen if we do the wrong experiment" (208). More specifically, they point out that while in the original interference experiment the interference pattern was evident just by tracking the results of a single detector, in the quantum eraser experiment the interference pattern was not evident if one only tracked this single detector. Now, given the lack of evidence of quantum behavior, at this point

> we might be tempted to argue that this is because the full experiment makes use of . . . macroscopic devices, subject to all the fluctuations which decoherence treats (i.e., the quantum behavior is destroyed because of the thermodynamic fluctuations of the larger environment). The quantum eraser experiment reveals that this, however, is not the case. *In reality the full quantum behavior is still present, but it can only be seen by performing a different measurement.* (Greenstein and Zajonc 1997, 209; italics mine)

(What was required to make the interference pattern evident upon the erasure of the which-path information was the tracking of two detectors together.) Furthermore, they point out why it is that we are so rarely able to detect the extant quantum behavior:

> Indeed, the effect of the [macroscopic device] here is not to wipe out quantum coherence. It is to entangle a photon arriving at the detector D with something else—with another photon arriving at [another detector] d2. Similarly, the effect of the incessant, fluctuating interactions to which all macroscopic detectors are subject is to entangle them with something else. In this case, however, the "something else" is far more complex. It is the rest of the world. The lesson of this experiment is that only if the right experiment could be performed, one which detects all the multitudinous components of this gigantic entangled state, could quantum behavior be seen.
>
> In the decoherence model . . . random disruption of the quantum state . . . leads to a loss of interference. But does the loss of interference mean that quantum coherence has been lost? This is the key issue addressed by the eraser experiment. If this disruption truly destroys quantum coherence, destroys it not just in practice but in principle, then it will be impossible ever to recover an interference signal. On the other hand, if the disruption leads rather to the creation of an entanglement, then the state has become more complex but its fundamental nature has not altered—it is a superposition, not a mixture. (Greenstein and Zajonc 1997, 209)

In other words, if we are clever enough, we may be able to detect the extant entanglement despite the fact that determinate values have been obtained in measuring a particular property. There is no physical collapse involved. What is at issue is the enactment of an agential cut, of a contingent separability within a phenomenon. Agential cuts enact the ontological determinacy within a phenomenon *and* the extension of entanglements that take place through measurement intra-actions.

6 QUANTUM MECHANICS AND COSMOLOGY: IS THERE A WAVE FUNCTION FOR THE UNIVERSE?

Since quantum mechanics is thought to be applicable at all scales, the question arises of how to apply quantum theory to cosmology. Since the 1960s, different attempts have been made to find a quantum theory of gravity. The accepted classical theory of gravity is Einstein's general theory of relativity. Constructing a quantum theory of gravity means understanding how to apply quantum theory to the general theory of relativity. This has proved exceedingly difficult. Questions have arisen as to whether there is not some intrinsic inconsistency that we meet in trying to paste the two theories together. The physicist Lee Smolin (2001) suggests that this difficulty is rooted in the fact that while standard quantum theory relies on a relation of externality between the measuring agencies and the measured system, this relation proves problematic when we turn to questions of cosmology because there simply is no outside to the universe for the measuring agencies to go to in order to measure the universe as a whole.[125]

> Among the things that we had to struggle with were the implications of the fact that the observer in quantum cosmology is inside the universe. The problem is that in all the usual interpretations of quantum theory the observer is assumed to be outside the system. That cannot be so in cosmology. (Smolin, 2001, 40) . . . What is needed is an interpretation of the states of quantum theory that allows the observer to be part of the quantum system. (ibid., 40, 42)

Bohr's interpretation is sometimes blamed for this difficulty.[126] However, I have argued that the relationship between "measuring agencies" and "measured system" is fundamentally different from the relationship of absolute externality that is a part of the classical worldview. Smolin succinctly summarizes the classical worldview on externality as a condition for objectivity:

> In science we are used to the idea that the observers must remove themselves from the system they study, otherwise they are part of it and cannot have a completely objective point of view. Also, their actions and the choices they make are likely to affect the system itself, which means that their presence may contaminate their understanding of the system.
>
> For this reason we try as often as we can to study systems in which a clean boundary can be drawn separating the system under study from the observer. That we can do this in physics and astronomy is one of the reasons why those sciences are said to be "harder." They are held to be more objective and more reliable than the social sciences because in physics and astronomy there seems to be no difficulty with removing the observer from the system. (Smolin 2001, 26)

This sentiment echoes Einstein's view on separability and objectivity. However, I have argued that this absolute condition of exteriority is not necessary to secure objectivity; objectivity may in fact be secured through agential separability, a relation of exteriority within the phenomenon. In Bohr's account, the agential cut delineates the "measuring agency" from the "measured object," but they are still *within* a particular phenomenon, that is, "parts" of a particular entangled state. So, contrary to the misconception that says that quantum mechanics requires the existence of an outside observer, we have seen that this is not the case. What does follow is that since there is no outside to the universe, there is no way to describe the entire system, so that description always occurs from within: *only part of the world can be made intelligible to itself at a time, because the other part of the world has to be the part that it makes a difference to.*

This seems very much in the same spirit as some of the new approaches to quantum gravity (e.g., loop quantum gravity [Isham], the relational quantum mechanics approach [Rovelli, Smolin, and Crane], and the context-dependent cosmological logic approach [Markopoulou-Kalamara]). Smolin writes:

> In all these theories there are many quantum descriptions of the same universe. Each of them depends on a way of splitting the universe into two parts such that one part contains the observer and the other part contains what the observer wishes to describe. . . . The quantum description is always the description of some part of the universe by an observer who remains inside it. (2001, 47–48)

As a result, "no observer inside the universe can see all of what is in the universe" (27).

CONCLUSIONS

The agential realist elaboration of Bohr's philosophy-physics that I offer takes many of Bohr's insights seriously while making explicit the implicit ontological dimensions of his theory and moving these insights away from their humanist grounding. Despite important differences between them, Einstein and Bohr share a belief in humanism. However, humanism is based on ontological and epistemological presuppositions that are challenged by the quantum theory. Einstein wants the human observer removed from the system of interest while Bohr insists on the constitutive role of the human observer in measurement observations, but both presume that the notion of the "human" is a well-defined concept that refers to an individually determinate entity with inherent properties, like the ability to engage in cognitive functions that make the universe intelligible. This presupposition has been an obstacle to resolving some of the long-standing foundational problems in the quantum theory, such as the Schrödinger cat paradox, the EPR paradox, and the measurement problem. Agential realism resolves these issues in a way that is consistent with recent theoretical and experimental developments. Like other recent interpretations of the quantum theory, it is based on a relational ontology.[127]

The agential realist account does not position human concepts, human knowledge, or laboratory contrivances as foundational elements of the quantum theory. On the contrary, rather than giving humans privileged status in the theory, agential realism calls on the theory to account for the intra-active emergence of "humans" as a specifically differentiated phenomena, that is, as specific configurations of the differential becoming of the world, among other physical systems. Intra-actions are not the result of human interventions; rather, "humans" themselves emerge through specific intra-actions. And measurements are not mere laboratory manipulations but causal intra-actions of the world in its differential becoming. This means that quantum theory has something to say about the ontology of the world, of that world of which we are a part—not as spectator, not as pure cause, not as mere effect. Humanism takes the human to be exceptional. My posthumanist elaboration of Bohr's account understands the human not as a supplemental system around which the theory revolves but as a natural phenomenon that needs to be accounted for within the terms of this relational ontology. This conception honors Bohr's deeply naturalist insight that quantum physics requires us to take account of the fact that we are part of that nature which we seek to understand.

EIGHT

The Ontology of Knowing, the Intra-activity of Becoming, and the Ethics of Mattering

Because believing a thing's true
can bring about that truth,
and you might be the shy one, lizard or electron,
known only through advances
presuming your existence, let my glance be passional
toward the universe and you.

—FROM ALICE FULTON, "Cascade Experiment"

Believing something is true doesn't make it true. But phenomena—whether lizards, electrons, or humans—exist only as a result of, and as part of, the world's ongoing intra-activity, its dynamic and contingent differentiation into specific relationalities. "We humans" don't make it so, not by dint of our own will, and not on our own. But through our advances, we participate in bringing forth the world in its specificity, including ourselves. We have to meet the universe halfway, to move toward what may come to be in ways that are accountable for our part in the world's differential becoming. All real living is meeting.[1] And each meeting matters.

CASCADE EXPERIMENT

In the great future—we can arrange the atoms the way we want; the very *atoms*, all the way down!

—FEYNMAN, "There's Plenty of Room at the Bottom"

Atoms aren't what they used to be. They aren't invisible, indivisible, immutable, impenetrable corpuscles running aimlessly in the void, constituting the sum total of existence; nor are they simply representative fictions, useful heuristics, or mere bookkeeping devices. Our evidence for the existence of atoms is multiple and robust, but it doesn't vindicate Democritus (nor any of the atomists up through the nineteenth century). Neither Democritus's atom nor his notion of realness, for that matter, survives today. Atoms have defied their inherited name—refusing the interpellative call of the mechanistic worldview. They simply aren't "uncuttable" little objects. And as for the famous void, well, it isn't all that is was supposed to be (or not be), either. According to quantum field theory, the vacuum is far from empty; indeed, it's teeming with the full set of possibilities of what may come to be. Matter is regularly created and destroyed. And the zoo of subatomic particles—including electrons, quarks, positrons, antiquarks, neutrinos, pions, gluons, and photons—isn't comprised of simple individual objects occupying specific positions in the vacuum we call space and time: not only is the very idea that they take up determinate positions in space not to be taken for granted, but part of their very nature seems to be wrapped up in the bubbling sea of possibilities that was to be but an inert backdrop for matter's passage. It's an ironic twist of history that the idea of an atom, proposed and adored throughout time for its simplicity (reducing diversity to order), is yielding such an intricate understanding of the nature of matter. It seems that the more fantastic our image of matter becomes, the more real it becomes (and vice versa).

As late as the end of the nineteenth century, many physicists were anti-realists in their stance toward atoms. Atoms were commonly held to be heuristic fictions, not bits of matter. Today scientists have no doubt that atoms are real. Not only do we have the means to "see" individual atoms, but we can pick them up, one at a time, and move them. Atomists as much as anti-atomists of yesteryear would no doubt be astonished by the technological feats we now regularly perform. Democritus's atom is not Newton's is not Dalton's is not Boltzmann's is not Einstein's is not Rutherford's is not Bohr's is not Feynman's. But this is not simply to say that the earlier images were wrong and we know better now, or that atoms are but social constructs that change as our ideas change. There's a much more interesting, and arguably more accurate, story to tell about this statement than either the naive realist account or the social constructivist account suggests. Not only has our image of the atom changed, but our practices of imaging and imagining and intra-acting with them have changed, and so have we.

During a *Morning Edition* program in the summer of 1996, the National Public Radio reporter Dan Charles pays a visit to the laboratory of the physicist Don Eigler at IBM's Almaden Research Center in the hills above San Jose, California. Charles sits down in front of a computer monitor and sets the stage for his audience as Eigler prepares to perform a maneuver at once of minute and gargantuan proportions:[2]

> *Dan Charles*: The equipment Eigler has rigged up makes this seem simple, a lot less complicated, really, than your standard video game. All he has to do is sit down at his computer screen and go to work with the computer's mouse.
>
> But this is no video game. Off in a different room, in a super-cooled vacuum chamber shielded from heat and vibration, Eigler is making a small change in the physical world, the most minute change possible.
>
> *Don Eigler*: IBM scientist on a power trip here. I'm going to move an atom.

If you want to pick up a single atom, you need a very small pair of tweezers, one that's on the scale of the object you want to move. The tool that Eigler uses is a scanning tunneling microscope (STM) that has a special microscope tip that is so sharp there is only a single atom at the end of it, just the right scale for either "sensing" or "grabbing" hold of an individual atom.[3] With a few clicks of the computer mouse, Eigler maneuvers the STM tip so close to a gadolinium atom sitting on the surface of a piece of niobium that it begins to bond with the gadolinium atom. He moves the tip sideways, pulling the gadolinium atom across the niobium surface to a new location, and then pulls the tip back, releasing the atom.[4] The listening audience is treated to a sonic display of the single-atom manipulation, courtesy of Eigler's clever connection of the STM to a stereo that converts the strength of the "tunneling current" (used to sense the presence of an individual atom) to an audible tone:[5]

> *Don Eigler*: OK, if you click on the left mouse button once, and we're out of the scanning mode. [sound of hum] See this little—an ounce of violet cursor here? That's where the tip is.
>
> Oh, this is what's really cool. Watch this. We're going to move to this atom. [hum increases] Hear the frequency go up a little bit right there? Down. Up. That's a tip riding up on top of the atom, and when the tip goes up, the sound goes up, the frequency goes up. Now comes the fun.
>
> [hum increases; sound of thumps] Ah, that was great. Every one of those thunks was the atom jumping from unit cell to unit cell across the surface, moving roughly one atomic diameter, and look, there it is—we moved it.

The proof is in the hearing. During the sideways tug of the gadolinium atom across the niobium surface, the audience hears distinct "thunks" as the atom is pulled across the unit cell structure formed by the spaces between the niobium atoms on the surface: that is, one can hear the atom being moved.

Then the NPR reporter Dan Charles is given a turn:

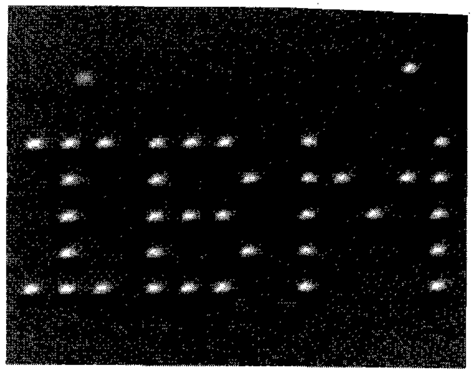
> *Don Eigler*: OK, now you're going to press and hold down the left mouse button. [sound of thump] You've got it. Try moving the mouse, holding the button down. [sound of thumps] OK. You've got the atom stuck over here on a step edge. That's OK. Let go. Oh, you still have it. Let go. See what happens.
> *Sound of thump*
> *Dan Charles*: There it is.
> *Don Eigler*: What you really need to see right now is the look on your face when you were moving an atom, and what you experienced while you were doing that is something that we experience also. It is the enormity of what you're actually doing, of just taking an atom and putting it where you want to go. You're controlling the structure of matter on the atomic level.

The interview with Eigler was the last installment in a three-part series on nanotechnology, and for those in the know, there was little surprise that Eigler was an honored guest.[6]

Don Eigler's fame as a nanotechnologist grows out of this remarkable discovery. Eigler and his colleague Erhard Schweizer reported their finding in an April 1990 issue of the journal *Nature*, where they dramatically displayed their achievement by using their STM to produce the world's smallest logo built from individual atoms (Eigler and Schweizer 1990). No one who has seen their image is likely to forget their institutional affiliation (see figure 30).[7]

In rearranging a few atoms on a surface, Eigler reconfigures our imaginations and the material possibilities for imaging, while undergoing his own set of transformations. A first-order phase change takes place as he is rapidly transformed into a new kind of expert—a nanotechnologist. Indeed, for some, he has become *the* emblematic nanotechnologist. And while nearly everyone in the nanotechnology business seems to have his or her own favorite promising candidate for how the future will be built, it is not at all surprising that Eigler's work sparked the immediate interest of nanotechnology enthusiasts who predict that humankind will be building machines and tools out of assemblages of individual atoms or molecules in the not-too-distant future. Eigler is a prime contributor to this stage of the new revolution, a fact that he explicitly acknowledges: "For decades, the electronics industry has been facing the challenge of how to build smaller and smaller structures. For those of us who will now be using individual atoms as building blocks, the challenge will be how to build up structures atom by atom."[8] The key to this future is not representing but intervening: not simply the imaging of atoms, but the ability to manipulate them.

The philosopher Ian Hacking's manipulability criterion for the reality of



30 The world's smallest logo, made out of thirty-five xenon atoms. A similar image, appropriately colored blue and titled "The Beginning," can be found in the IBM STM image gallery. This is now just one of many images of atom arrangements created with a scanning tunneling microscope (see, for example, the IBM STM image gallery on their website). *Reprinted with permission of IBM Research, Almaden Research Center.*

atoms seems at once on the mark and already dated by new technological advances. Recall that Hacking argues that while scientists need not take the objects of their investigations to be real, they have no choice but to believe in the reality of the tools that they use to manipulate objects: "Experimenting on an entity does not commit you to believing that it exists. Only *manipulating* an entity, in order to experiment on something else, need do that" (Hacking 1983, 263).[9] But the example of atom manipulation by an STM makes Hacking's claims for entity realism seem far too timid. What would be the justification, in this case, for any less confidence in the reality of the objects as opposed to the tools used to manipulate them? More to the point, what this example brings to the fore is the need to call into question the determinate category designations of "tools" and "objects" that Hacking's formulation assumes. Indeed, the lack of a fixed object-apparatus distinction is key to Eigler's group's ability to manipulate atoms.

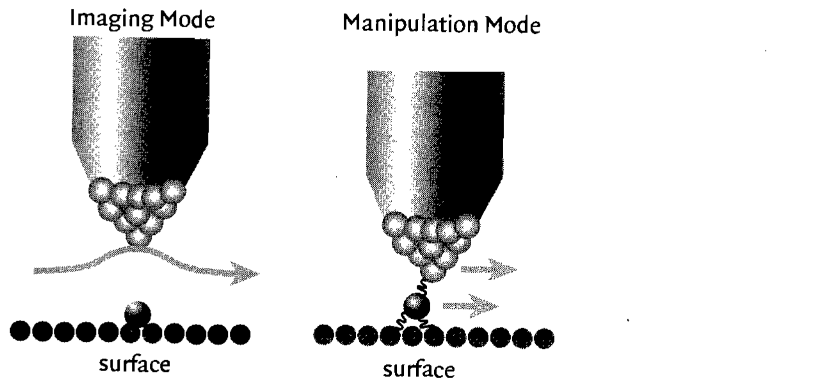
According to Eigler, "Atom manipulation came about almost by accident" (1999, 430). Encountering some "unusual streaks" across the STM images they were producing, Eigler and Schweizer decided to investigate. They found that the presence of the streaks was related to the operation of the microscope. If they brought the tip of the microscope sufficiently close to the sample, then streaks would appear. Eigler says that "this immediately suggested that we could use the tip to control the position" of the individual atoms (431), and so they set out to do just that:

> Trying out our ideas required modifications to the software we used to operate the microscope. Within a day the necessary modifications were made. These modifications allowed us to switch from an imaging mode where the

> tip executed a raster scan of the surface, to a mode in which we could move the tip of the microscope along any desired path across the surface, and with a tunnel current different from that used for imaging. With these modifications in place, I began by imaging an isolated xenon atom which was bound to a defect site on the platinum surface. I then stopped imaging, moved the tip directly over the xenon atom, increased the magnitude of the tunneling current in order to bring the tip a little closer to the xenon atom, and then I had the computer move the tip from the location where the xenon atom originally was to a new location not too far away. Once the tip reached the new location, I reduced the magnitude of the tunnel current in order to increase the separation between the tip and the xenon atom and thus return to the imaging mode. Next, I re-imaged the surface to find that the xenon atom had been successfully moved to the location of my choice. I then repeated the same experiment four times, and it worked each time. With this xenon atom, the milestone was achieved. (431–32)

Switching back and forth between imaging and manipulation modes, Eigler and Schweizer were able to both move individual atoms *and* demonstrate that that was in fact what they were doing (see figure 31). That is, in the hands of Eigler and Schweizer, the STM became a device for moving and for proving, for "intervening" and "representing" (to use Hacking's old terms).

Significantly, imaging and manipulating are complementary, that is, mutually exclusive modes of operation. In imaging mode, the "adatom" (in this case the xenon atom) is part of the surface being imaged (i.e., the object); whereas in manipulation mode, the "adatom" becomes part of the microscope tip (i.e., the agencies of observation). In fact, in the time-honored tradition of enlisting the sense of sight (and its limits) as a metaphor for knowing, Eigler invokes the well-worn example of the blind person with a cane to help convey the "haptic" sense of knowing that comes from operating an STM.[10] On Eigler's reckoning, STM imaging is akin to the practice of "cane traveling," the skillful practice a blind person uses to "see" or grasp the terrain. This is reminiscent of the example Bohr uses to help a general audience understand complementarity and Merleau-Ponty uses to describe the nature of embodiment (see discussion in chapter 4). Recall that Bohr's discussion focuses on two possible complementary practices: on the one hand, the man can hold the cane tightly so that it functions as an instrument of observation (an extension of the person trying to negotiate the room); on the other hand, he can hold it loosely so that it becomes an object of observation.[11] The cane is neither inherently part of the object nor the agencies of



31 Eigler and his colleagues reconfigured the STM so that they could switch back and forth between "imaging mode" (*left*) and "manipulation mode" (*right*) by changing the tunneling current. In imaging mode, the adatom sits on the surface and is imaged by the STM. In manipulation mode, the tunneling current between the adatom and the tip is increased, and the tip is used to move the adatom along the surface. *Illustration by Nicolle Rager Fuller for the author.*

observation. The line between subject and object is not fixed and it does not preexist particular practices of their engagement, but neither is it arbitrary. Rather, object and subject emerge through and as part of the specific nature of the material practices that are enacted.[12]

For Bohr, the relation between knower and known is much more intimate than either the notion of intervention or even the shift from sight to touch suggests: distance is not a prerequisite for objectivity, and even the notion of proximity takes separation too literally. Bohr argues that quantum physics teaches us that the belief in an inherent fixed Cartesian distinction between subject and object is an unfounded prejudice of the classical worldview, and that the acknowledgment of the inherent indeterminacy of object and apparatus, the material resolution of the indeterminacy, and the inseparability of their relation as it is materially enacted constitute the very possibility for understanding quantum phenomena objectively. Hacking's notion of intervening simply doesn't cut it. Against Hacking's "Don't just peer, interfere," an alternative motto might be "Not simply intervene, enact the between." Intra-acting, not merely intervening, is entailed in both experimental and theoretical practices.

What could be a more compelling emblem of the triumph of the scientific enterprise and its claims to scientific realism than the world's smallest corporate logo? Indeed, on the surface, the mini-IBM logo appears to be nothing less than the most literal incarnation imaginable of representationalism's claim of the one-to-one correspondence between words and things—the logos made flesh in its most base form, as if the result of some youthful naïveté that has mistaken the metaphoric for the literal. Arguably, however, this image marks the limits, rather than the confirmation, of this belief system. As one reporter commenting on one of Eigler's images aptly notes: "One almost could envision the cursive writing of René Magritte under the image: 'Ceci n'est pas un atom.'"[13] As with Magritte's famous painting *Ceci n'est pas une pipe*, the point is not that it really isn't a pipe but only a representation of a pipe, but rather that representations do not simply refer in ways that we have come to expect, that in fact the entire question of referentiality seems to have lost its self-evidentiary nature and givenness has lost its transparency, and we can no longer see our way through the game of smoke of mirrors that representationalism has become. Like a good magician, representationalism would have us focus on what seems to be evidently given, hiding the very practices that produce the illusion of givenness.

Although the STM images in the IBM gallery were created at temperatures near absolute zero so that the atoms placed in specific locations stick to the surface (and to our imaginations) "like little refrigerator magnets," they are not snapshots of preexisting things frozen in time—caught in the act as it were—but rather condensations of multiple material practices across space and time. Reading the phenomena—the difference patterns through which space, time, and matter come to be—including all the various apparatuses that help produce the illusion of the self-evidentiary nature of "the given" allows the frozen images to thaw out and the subject matter to come alive. The entangled sets of practices that go into making these images include: STM microscopes and practices of microscopy, the history of microscopy, scientific and technological advances made possible by scanning tunneling microscopes, the quantum theory of tunneling, material sciences, IBM's corporate resources and research and development practices, scientific curiosity and imagination, scientific and cultural hopes for the manipulability of individual atoms, Feynman's dream of nanotechnologies, cultural iconography, capitalist modes of producing desires, advertising, the production and public recognition of corporate logos, the history of the atom, the assumption of metaphysical individualism, complex sets of visualizing and reading practices that make such images intelligible as pictures of words and things, and the intertwined histories of representationalism and scientific practice. And this is merely an abbreviated list that doesn't even scratch the surface

when it comes to the kinds of genealogies that are needed to give an objective accounting of the micrograph. This is not to say that each particular scientific practice includes everything under the sun, but rather "only everything relevantly interrelated" (Rouse 2002, 283). What is required is a joint effort that relies on multiple forms of literacy to make explicit the different apparatuses that are a part of the phenomenon being investigated (see Barad 2000).

In my agential realist account, scientific practices do not reveal what is already there; rather, what is "disclosed" is the effect of the intra-active engagements of our participation with/in and as part of the world's differential becoming. Which is *not* to say that humans are the condition of possibility for the existence of phenomena. Phenomena do not require cognizing minds for their existence; on the contrary, "minds" are themselves material phenomena that emerge through specific intra-actions. Phenomena are real material beings. What is made manifest through technoscientific practices is an expression of the objective existence of particular material phenomena. This is, after all, a realist conception of scientific practices. But unlike in traditional conceptions of realism, "objectivity" is not preexistence (in the ontological sense) or the preexistent made manifest to the cognitive mind (in the epistemological sense). Objectivity is a matter of accountability for what materializes, for what comes to be. It matters which cuts are enacted: different cuts enact different materialized becomings.[14]

Once it becomes feasible to manipulate individual atoms, the possibilities for making new configurations of atoms open out before us. In fall 2002, Don Eigler was back on National Public Radio talking about his lab's latest achievement. Ira Flatow, NPR science correspondent and host of *Talk of the Nation: Science Friday*, sets the stage:[15]

> *Ira Flatow*: How small can computers get? Just about every computer chip maker is trying to shrink their chips or to pack more power into the same size space, and last week in the online edition of the journal *Science*, researchers at IBM reported that they have built what they're calling the smallest computer chip circuit yet—one bil . . . one trillionth, that's one *trillionth* of a square inch—and to get it that small they had to make it out of individual molecules. Now the device is slow, it's impractical, but it can perform some of the basic operations for computing and it does it in a space about 260,000 times smaller than the most advanced silicon chips.[16]

Eigler explains that they are able to build operating logical circuits using a "molecule cascade," which they set up and initiate with their STM.[17] The analogy he draws is to the familiar cascading of dominoes:

> *Don Eigler:* "[It's] like playing with dominoes. You can imagine how you can set up a row of dominoes and then when you topple an initial domino it causes the whole chain of dominoes to fall over sequentially. We've done something just like that, but imagine instead of something as large as a domino, that the domino is made up out of, in our case, just two atoms forming a carbon monoxide molecule. And then by laying out the carbon monoxide molecules we can topple the first one sort of by hand, with the best hand we have that let's us interact with atoms, and then away it goes . . .

The "dominoes" are set up and the "topple" is initiated using the IBM researcher's "set of hands to the world of atoms and molecules"—a scanning tunneling microscope.

Taking in this latest development, one gets the distinct impression that this "cascade" experiment is not only a miniature mechanism for making computers on a scale that may soon leave silicon technologies in the dust, but also a metaphor for the increasingly rapid development of nanotechnologies that awaits us. But matter and meaning, the literal and the figurative, are never as separate as we like to pretend, and therefore no argument will be able to arrest the expanding public sentiment that the cascade experiment is much more than a metaphor, that the tiniest changes, rearrangements in the configurations of atoms, hold the literal potential to tunnel across different scales of space, economy, and imagination, that they may initiate a chain reaction in the not-too-distant future that will fan out and explode into a host of new technologies and reorganizations of power connecting the most minute to the most gargantuan. Nanotechnologies have been characterized by the refrain that anything that already exists on the horizon of our imaginations is already too limited a projection of the new sciences' potential. If Foucault is correct in his assessment that power operates through the specific constitution of bodies and subjectivities, then nanotechnologies have the potential to reconfigure the materiality of our being all the way down to the very atoms of existence, and beyond, to a point where individuality is itself undone by the specific entanglements of becoming that transcend the distinctions between bios and technics, organic and inorganic, artificial and natural, mind and body. Foucault's "microphysics of power" would not simply be operative at the scale of individual atoms; scale itself would be iteratively reconstituted as spacetimematter is reconfigured.

"NanoQuébec," a Canadian nonprofit organization committed to the development and commercial application of nanotechnologies, is but one of a growing number of appellations that visually perform a society's investment in re(con)figuring economies of scale, from the minute to the global. Not only are nation-states willing to consider reconstituting themselves in alignment with atomic reconfigurings, but no scale seems too large or small to conquer. Aerospace engineers, for one, are champing at the bit to learn from Mother Nature her secrets to molecular design that will enable machines to sense their environments, reproduce and disperse themselves, and carry out self-repair and regeneration, expanding the frontiers of exploration well beyond our solar system. Machines will generate new life; life will be reworked. The nanoscale is the scale of life processes, and the combination of computational nanotechnology and bio-nanotechnology foretells the possibilities of neuroelectronic interfaces that use nanodevices to join computers to the human nervous system. With one hand on a computer mouse and an eye to the future, not only do we make changes to configurations of individual atoms, but the very nature of who "we" are begins to shift. Our imaginations, bodies, desires, organizational structures of research and investment, and much more quake with the expectation of the impending "nano-tsunami" that portends immense changes to life on earth and beyond. "The economic potential [alone] of this new field of activity is dizzying. Studies estimate that the world nanotechnology annual market could reach more than a trillion dollars within twelve years."[18]

Already the potential of these new developments is generating new international and transnational configurations of university, industry, and government laboratories. Knowledge and product making are being reconfigured. The authors of a popular book on nanotechnology note that the "fusion of interdisciplinary knowledge coming together at the nanoscale will be one of the great benefits nanoscientists will introduce into our lives."[19] Those who would offer a requiem for physics while touting the new supremacy of the biological disciplines have failed to appreciate the transdisciplinary networks of knowledge and product making—transcending the divisions between physical, biological, and engineering disciplines—that are being (re)configured at a pace that humanities proponents of transdisciplinarity only dream about. The National Nanotechnology Initiative (NNI) website already boasts dozens of nanotechnology centers sponsored by the National Aeronautics and Space Administration (NASA), the National Science Foundation, the Department of Defense, and the Naval Research Laboratories.

It appears that the branching chain reaction has already been initiated and that ethical, legal, and social considerations seem destined to be forever behind the curve of cascading technological advances. But there is more to causality than the runaway scenario that unfolds in deterministic fashion.

Dominoes are surely not what Alice Fulton had in mind in her poem "Cascade Experiment," with its ethico-onto-epistemic attention to our responsibilities not only for what we know but for what may come to be. A cascade in Fulton's sense is not a serial chain of consequences, an inevitability set in motion by some initial act, but an iterative reconfiguring of possibilities entailed in our passional advances toward the universe.

BIOMIMICRY, MIRROR IMAGES, AND THE OPTICS AND POLITICS OF REFLECTION

> Silently and efficiently, the new team member toils away in a chemistry lab at the University of California at Santa Barbara. With perfect precision, she lays down an ultrathin layer of an organic substrate. Onto this, she deposits interlocking calcite crystals, atom by atom. The two layers bond into a delicate crystal lattice. Under a microscope, it calls to mind the flawless thin-film layers on a silicon chip.
>
> But there is no clean room, vacuum chamber, or chip gear in this lab, where professors Galen D. Stucky and Daniel E. Morse brainstorm new materials. For that matter, the "team member" is no ordinary staff researcher. She's a mollusk—an abalone. And like so many of nature's creations, she has acquired, through millions of years of evolution, an exquisite form of molecular machinery to create her shell—machinery that leaves today's best fabrication tools in the dust.
>
> —NEIL GROSS AND OTIS PORT, "The Next Wave for Technology"

"The only true nanotechnologist today is Mother Nature," explains Michael Roukes, a California Institute of Technology physics professor, "but slowly humans are learning to mimic her handiwork."[20]

In her 1997 book entitled *Biomimicry: Innovation Inspired by Nature*, the nature writer and conservationist Janine Benyus names "an emerging discipline that seeks sustainable solutions by emulating nature's designs and processes."[21] According to Benyus, biomimicry marks the beginning of a new postindustrial era: "Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her." Benyus has received several awards, including the Rachel Carson Environmental Ethics Award. She is the cofounder of the Biomimicry Guild, which brings biologists, industrialists, inventors, and designers to the drawing board, teaching clients that include Nike, Hewlett-Packard, and Novell to draw inspiration from nature to solve

human problems. Biomimicry is being hailed as nothing less than an answer to Rachel Carson's *Silent Spring*, but even biomimicry's strongest proponents, Benyus included, acknowledge that, like other technologies, it will not necessarily be spared the dangers of misuse and abuse:

> Biomimics develop a high degree of awe, bordering on reverence. Now that they see what nature is truly capable of, nature-inspired innovations seem like a hand up out of the abyss. As we reach up to them, however, I can't help but wonder how we will use these new designs and processes. What will make the Biomimicry Revolution any different from the Industrial Revolution? Who's to say we won't simply steal nature's thunder and use it in the ongoing campaign against life?
>
> This is not an idle worry. The last really famous biomimetic invention was the airplane (the Wright brothers watched vultures to learn the nuances of drag and lift). We flew like a bird for the first time in 1903, and by 1914, we were dropping bombs from the sky. (Benyus 1997)

Mimicry is the highest form of flattery, or so the saying goes. Perhaps this familiar adage provides a clue to why biotech companies might be interested in biomimesis, not only as a method but as camouflage against the prying eyes of would-be critics. Some biotech companies have already enlisted biomimesis in their attempts to hoist themselves above the murky pool of ethical, legal, and social concerns, posing as benign inventors, if not downright all-natural Mother Nature–loving sustainability advocates. Camouflage, of course, is nature's own biomimetic technology, imitated and popularized by the military during World War I. Imitating imitation is nothing new, but the forms mimesis is taking are.

A Canadian biotech company recently purchased a decommissioned U.S. Air Force base on the American side of the border just outside Plattsburgh, New York, to farm genetically engineered Spidergoats, thousands of them; but Jeffrey Turner, founder, president, and CEO of Nexia Biotechnologies, isn't interested in cloning goats per se.[22] Referring to Dolly as a "scientific stunt," Turner explains to one reporter that "Nexia's project is less about altering nature than harnessing it. The company's goal isn't to create weird goats; they're merely a means of producing useful quantities of spider silk, a simple substance created eons ago by natural evolution. . . . What Nexia is really up to isn't mere genetic engineering, it's 'biomimicry.' "[23] Spider silk is the holy grail of material sciences—it's five times stronger than steel and stretches 30 percent farther than most elastic nylon—with a host of medical, industrial, and military applications, including biodegradable sutures for surgery, replacement ligaments or tendons, industrial fibers, and bullet-proof vests. There are even recreational applications like fishing line and tennis racket strings. Even the haute-couture fashion world is already salivating over the possibilities of spinning new fabrics.

"It's way beyond anything we humans can make. Milled steel pales next to it." Turner is awed by the ingenious engineering talents of the spider, which, he explains, were honed by the competitive pressures of nature's own military exploits: "The spider's evolution comes out of a kind of arms race between spiders and bugs. The bugs start flying to get away from spiders, so the spiders have to come up with a new weapon." Well, then, what could be more natural than scientists at the Canadian biotech company Nexia teaming up with the Materials Science Team of the U.S. Army Soldier Biological Chemical Command to take some lessons from spiders? (Who's copying whom? Is copying ever not a form of self-replication? When it's all done with mirrors, it's difficult, if not impossible, to find out who's really spinning the sticky web.) Emulating not only nature's best ideas for peaceful coexistence but also its ingenuity in the face of military challenges, this is taking nature as inspiration to a new level. And much like the envious fecundity of Mother Nature's symbiotic relationships, the relationship between Canadian-based Nexia and the U.S. military is proving to be very productive indeed. In the January 2002 issue of the journal *Science*, this international interdisciplinary industrial-military hybrid team announced a major materials-science breakthrough: a way to spin silk from goat's milk (Lazaris et al. 2002). The implications and the payoff from this research are potentially enormous. Nexia now holds the patent on a recombinant spider silk, trade-named BioSteel®, and it is moving rapidly toward commercial development. BioSteel®, according to the company and its promoters, has the additional advantage of being eco-friendly in both its composition (it is biodegradable) and its production process (which is water based), as opposed to most other synthetic fibers.[24]

So while Nexia is busy making recombinant spider silk for a host of medical, military, and industrial applications by taking genes from golden orb-weaving spiders and putting them into fertilized goat eggs so that the goat will secrete spider silk into its milk, which can be profitably harvested by the company, Turner is spinning the yarn, flattering the spider's talents for manufacturing a materials-science wonder—"a self-assembling, biodegradable, high-performance, nanofiber structure one-tenth the width of a human hair that can stop a bee traveling at 20 miles per hour without breaking."[25] And so it shouldn't surprise us that when Jeffrey Turner is asked the "big-E" ethics question that many biotech company execs treat with great annoyance, as if such questions are pesky little black flies that keep swarming no matter what public relations repellent is applied, he responds with the confidence of a jujitsu master, smiles at the futility of fly swatting, and instead uses the fly's own energy, working in concert with the spider, to outwit the flies at their own game: with great aplomb, Turner calmly mimics the "biomimicry" biomimics. What could be more natural than taking nature as inspiration? Even nature does it. No wonder Jeffrey Turner claims to be a practitioner.

Benyus is well aware of the potential for the misuse of biomimicry. In fact, she points specifically to Nexia's transgenic "mimicking" (the quotation marks are Benyus's) of spider silk, which turns goats into "cheap factories" (this description is Turner's), as a case in point:[26] "Every fiber of my being cries when I hear that. That's the antithesis of the kind of respect, the maturity that we need. So I think in terms of what we shouldn't be doing, I think this transgenic engineering is the height of hubris. It's a biological transgression of the worst kind."[27]

Benyus has a principled complaint against transgenic engineering: nature doesn't do it—nature doesn't trade genes across classes of organisms—and so we shouldn't, either. That is, Benyus advocates adopting nature not only as model but also as mentor and measure: "If nature as model says, 'What would nature do here?' nature as measure says, 'What wouldn't nature do here?' " (ibid.). In other words, Benyus's ethical principle for biomimicry is biomimetic: "Biomimicry says: if it can't be found in nature, there is probably a good reason for its absence. It may have been tried, and long ago edited out of the population. Natural selection is wisdom in action."[28]

Now, the suggestion of an ethics based on the principle of following nature's lead will no doubt sound like an all-too-familiar drone for some, and for good reasons. Natural law arguments for social policy abound, and there are copious examples of misguided attempts to enlist nature as a justification for every possible social prejudice, including racism, sexism, and homophobia. Social Darwinism is a well-known example illustrating the dangers of biomimicry as a social or ethical principle. Going back to Friedrich Engels, critics of social Darwinism have argued that Darwin takes his inspiration from social and economic doctrines based on competition and survival of the fittest, reads them into nature, and then social theorists use Darwin's "nature" to justify social policy based on natural selection, saying that they are simply taking their inspiration from nature.[29] But the dangers of entering this house of mirrors have not escaped Benyus, who explicitly warns against taking our ethical principles from the natural world:

For people as they did during the period of Social Darwinism to look to the natural world to figure out who should live and who should die or who should breed—that's really, really dangerous, I think. Because how other organisms are being judged by natural selection and the kinds of societies that they've knit together, we can't pick a species and say we should be more like that. I think looking to nature for our mores and our ethics and our morality is really dangerous. We are a unique species, an ethical moral animal, and there are some places that it just doesn't fit.[30]

This advice—to look to nature as an ethical measure but not as a basis for our ethical principles, "to judge the rightness of our innovations" based on nature's designs but not to judge the rightness of our actions based on nature's way of doing things—seems reasonable enough at first glance. However, this principle ultimately falters on the very issue that the example of social Darwinism brings to light: how are we to understand the notion of "nature" that is being invoked? Benyus's principle relies on a belief in human exceptionalism and a hard distinction between nature and humans: we humans are a species unique in all the animal kingdom by virtue of our ethical character; we are historical creatures; while nature, on the other hand, has a givenness that is outside of culture; nature is found in the rain forest and the swamp, environments threatened by (nonindigenous) human culture(s). Furthermore, Benyus's distinction seems to presume that designs are simply transparently there in a way that actions may not be, that we have an immediate access to nature's designs in a way that gets clouded when we turn to observing behaviors, that material designs can be separated from the agential practices that produce them. This presumption that there is a pure nature separate from culture operates throughout Benyus's work. As with all mirroring practices, biomimicry has a built-in optics based on a geometry of distance from that which is other. But is there a "pure nature" (both epistemologically and ontologically speaking) to which we can turn for inspiration? And how pure is this implied notion of purity when its invocation throughout history has helped to perpetuate some of the most heinous crimes known to humankind? (Isn't the very notion of "race" nothing save the notion of "purity" put into practice?) Furthermore, and with astonishing irony, the discourse of nature as separate from culture seems strikingly out of step with the very practices of biomimetics, which, not incidentally but rather by virtue of its own principles, actively reworks the boundaries between nature and culture. And isn't the undoing of the very idea of an inherent nature-culture boundary a useful tool, if not a prerequisite, for destabilizing sexism, racism, and homophobia and other social ills that are propped up by this dualism and its derivatives? It is ironic that while environmental activists are busy reifying a notion of nature based on purity, with all its problematic implications, the enterprise of bioengineering is making it crystal clear that the nature-culture dualism is a construction, a point that feminists and other social critics have been trying to get across for some time. What is at issue and at stake is "what counts as nature, for whom, and at what costs" (Haraway 1997, 104).[31]

This is not an argument for or against biomimetics or other technoscientific practices writ large. On the contrary, the point is that these practices hold both incredible promise and unfathomable dangers. Which is not the end point but the beginning point for ethical considerations.

DIFFERENCES THAT MATTER: DIFFRACTIONS, DIFFERENTIAL EMBODIMENT, AND THE ONTOLOGY OF KNOWING

> The "eyes" made available in modern technological sciences shatter any idea of passive vision; these prosthetic devices show us that all eyes, including our own organic ones, are active perceptual systems, building in translations and specific ways of seeing, that is, ways of life. There is no unmediated photograph or passive camera obscura in scientific accounts of bodies and machines; there are only highly specific visual possibilities, each with a wonderfully detailed, active, partial way of organizing worlds. . . . Understanding how these visual systems work, technically, socially, and psychically ought to be a way of embodying feminist objectivity.
>
> —DONNA HARAWAY, *Simians, Cyborgs, and Women*

"Eyeless Creature Turns Out to Be All Eyes," announces the *New York Times*. The *Times* article summarizes the results of a study published in the August 23, 2001, issue of the scientific journal *Nature*, in which an international team of material scientists, theoretical physicists, chemists, and biologists report their amazing finding that the brainless and eyeless creature called the brittlestar, an invertebrate cousin of the starfish, sea urchin, and sea cucumber, has a skeletal system that also functions as a visual system.[32]

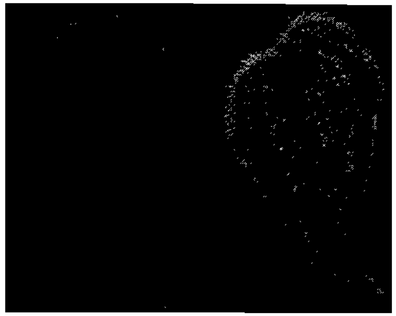
> The brittlestar, a relative of the starfish, seems to be able to flee from predators in the murky ocean depths without the aid of eyes. Now scientists have discovered its secret: its entire skeleton forms a big eye. A new study shows that a brittlestar species called *Ophiocoma wendtii* has a skeleton with crystals

that function as a visual system, apparently furnishing the information that lets the animal see its surroundings and escape harm. The brittlestar architecture is giving ideas to scientists who want to build tiny lenses for things like optical computing.

The researchers found that the approximately ten thousand spherically domed calcite crystals covering the five limbs and central body of the brittlestar function as microlenses, and that the microlenses collect and focus light directly onto nerve bundles that are part of the brittlestar's diffuse nervous system. Remarkably, the brittlestars secrete this crystalline form of calcium carbonate (calcite) and organize it to make the optical arrays. According to Dr. Alexei Tkachenko of Bell Laboratories, one of the authors of the study, "The brittlestar lenses optimize light coming from one direction, and the many arrays of them seem to form a compound eye" (quoted in the *Times* article). "It's bizarre—there's nothing else that I know of that has lenses built into its general body surface," says Michael Land, who studies animal vision at the University of Sussex in Brighton, England.[33]

The fact that certain species of brittlestars respond to light was already well established, but the mechanism of their superior visual capacity was not known.[34] These photosensitive brittlestars are able to navigate around obstacles, flee from predators, and detect shadows. They also turn lighter in color at night and darker during the day (see figure 32). At first glance, this evolutionary strategy seems ill conceived, since it increases their visibility to predators. But if the brittlestar's goal is to increase its vision (the better to avoid predators), to collect as much light as possible during the night, and likewise to protect its visual system from oversensitivity, overexposure to light, during the day (the better to put on "sunglasses"), then nature's selective process seems justified.

To test their hypothesis that "these calcitic microstructures might have a function in directing and focusing the light on photosensitive tissues" (Aizenberg et al. 2001, 820), the researchers at Bell Labs used a technique called optical lithography, which is a process also used for inscribing circuits on microchips: "To detect and visualize the lensing effect, we designed a lithographic experiment. A DAP [dorsal arm plate] of *O. wendtii* [one of the species that exhibit photosensitivity] was cleansed of organic tissue, and a low-magnification scanning electron micrograph (SEM) of its dorsal surface was recorded as a reference image." Figure 33a shows the SEM of the dorsal arm plate cleansed of organic material; in figure 33b, the SEM (using greater magnification) of the peripheral layer of a dorsal arm plate clearly shows the lens structures of *O. wendtii*.



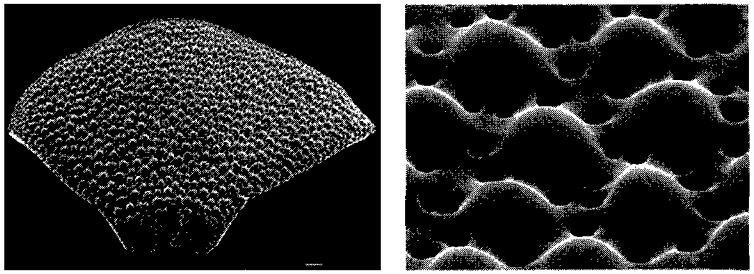
32 Photosensitive brittlestar. From J. Aizenberg et al., "Calcitic microlenses as part of the photoreceptor system in brittlestars," *Nature* 412 (2001): 819, figure 1b. *Reprinted with permission of Macmillan Publishers Ltd. Images courtesy of Nature Publishing Group, London.*

The lensing system was analyzed by placing the prepared sample on a silicon wafer. Mimicking the process used to optically engrave circuits on a silicon wafer in the making of microchips, the researchers shined light through the lenses, etching the photosensitive wafer. By analyzing the etchings, the researchers were able to deduce the focal length of the lenses. This was compared to a transmission electron microscopy study of thin sections of decalcified dorsal arm plates, which revealed *bundles of nerve fiber located precisely at the focal plane of the lens system*. On the basis of this finding, the researchers offered the following conclusion: "We suggest that the array of calcitic microlenses with their unique focusing effect and underlying neural receptors may form a specialized photoreceptor system with a conceivable compound-eye capability" (Aizenberg et al. 2001, 821).

In talking with the press, Joanna Aizenberg, a Bell Labs scientist and the lead author of the study, also makes use of the more high-tech comparison to a digital camera that builds up a picture pixel by pixel.[35] In this exchange, one quickly loses track of whether the digital camera is a metaphor for brittlestar vision or the reverse, especially as the metaphor begins to take on a strikingly material form:

> Instead of trying to come up with new ideas and technology, we can learn from this marine creature. . . . The [calcitic] lenses surround the whole body, looking in all different directions and providing peripheral vision to the organism. . . . This is the quality we all want to incorporate in optical devices, in cameras in particular. Instead of having one lens pointing in one direction, you could have thousands of lenses pointing in different directions. This will give you perhaps a 360-degree view of the whole space.[36]

In summary, the remarkable finding of this international multidisciplinary team of scientists is that the brittlestar's skeletal system is composed of



33 The image on the left (*a*) shows a scanning electron micrograph (SEM) of the dorsal arm plate of a brittlestar (*O. wendtii*); the image on the right (*b*) is an SEM (increased magnification) showing calcite lenses on the peripheral layer of a dorsal arm plate skeletal section. From J. Aizenberg et al., "Calcitic microlenses as part of the photoreceptor system in brittlestars," *Nature* 412 (2001): 819, figures 1c and 1f. *Reprinted with permission of Macmillan Publishers Ltd. Images courtesy of Nature Publishing Group, London.*

an array of microlenses, little spherical calcite crystal domes (on the order of tens of microns in diameter) arranged on its surface, which collect and focus light precisely on points that correspond to the brittlestar's nerve bundles, part of its diffuse nervous system, suggesting that the combined system seemingly functions as a compound eye (an optical system found in insects).

Roy Sambles, a physicist who works on optics and photonics at the University of Exeter in England, expressed his enthusiasm for this brainless creature's ingenuity:

> It's astonishing that this organic creature can manipulate inorganic matter with such precision—and yet it's got no brain. It's starting with a soup of chemicals and pulling out this wonderful microstructure.[37]

> Human ingenuity came up with microlens arrays only a few years ago, and they are used in directional displays and in micro-optics, for example as signal-routing connectors for signal processing. Once again we find that nature foreshadowed our technical developments. The same applies to photonic solids, structures that can selectively reflect light in all directions. Photonic materials have stimulated much research over the past ten years because of their potential in light manipulation, yet they are to be found in opals and in the wings of butterflies. But then, nature has been in the business of developing functioning optical structures for a very long time.[38]

The brittlestar may not get full credit for its superior ingenuity, which exceeds the current technological ingenuity of humans, but a larger, older, and

wiser configuration called "nature" does. As one National Public Radio reporter put it: "Even the most primitive creatures might have the edge over modern science."[39] (So what makes it "primitive" again?)

While this discovery is a fantastically interesting scientific result, it's probably fair to say that the excitement surrounding this finding and the wide reporting of this story have more to do with its potential applications than with pure amazement at the ingenuity of the brittlestar's bodily know-how. Consider the appropriately measured tone of the acknowledgment in the technical article's closing sentence:

> The demonstrated use of calcite by brittlestars, both as an optical element and as a mechanical support, illustrates the remarkable ability of organisms, through the process of evolution, to optimize one material for several functions, and provides new ideas for the fabrication of "smart" materials. (Aizenberg et al. 2001, 821)

Understatement (or least reserve) is considered good professional etiquette in scientific publications, and while summaries such as the ones in the "News and Views" section of *Nature* allow quite a bit more leeway, statements to the popular press follow a different set of rules altogether. So it perhaps isn't surprising that a *Discover Magazine* reporter juxtaposes a statement by Aizenberg expressing her amazement at the brittlestar with a pull-no-punches opening line that makes the stakes crystal clear:

> Until now, engineers have only dreamed of such perfect microlenses, which could be invaluable in optical networking and microchip production. Aizenberg is inspired. "This is very clever engineering," she says. "We may be able to mimic it, borrowing from nature a design that has already been working for thousands of years."[40]

As might be expected, the press releases from Bell Labs (owned by Lucent Technologies) are very upbeat about the discovery. A press release dated August 22, 2001, entitled "Bell Labs scientists find remarkable optics in marine creatures that may lead to better microlenses for optical networks," explains that this multifunction biomaterial may lead to better-designed optical elements for telecommunications networks and faster computers through improved optical lithography techniques:

> Scientists hope to mimic nature's success and design microlenses based on the brittlestar model. Such biomimetic lenses may prove useful as components of optical networks, and in chip design, where they could potentially improve optical lithography techniques. "Biomimetics builds on nature's

expertise," said John Rogers, director of nanotechnology research at Bell Labs. "In this case, a relatively simple organism has a solution to a very complex problem in optics and materials design."

A year and a half later, on February 21, 2003, Bell Labs issued an enthusiastic report on Aizenberg's latest achievement, published in the journal *Science*: "the creation of the world's first micro-patterned crystals inspired by bioengineering found in nature" (Aizenberg et al. 2003). The summary phrase, written in bold under the title and designed to catch the reader's eye, is telling: "Study of how nature designs crystals in sea organisms may be important to nanotechnology." With a wink to the brittlestar, in a show of reverence that resembles the kind of respect for nature that Benyus exudes, Aizenberg explains the project thus:

> I have always been fascinated with nature's ability to perfect materials. . . . The more we study biological organisms, the more we realize how much we can learn from them. We recently discovered that nature makes excellent micro-patterned crystals, and we decided to see if we could copy the natural approach in the lab, since this technique may be useful in nanotechnology.

In contrast to the "top-down" approach currently used to make lenses, whereby glass is ground down to match the specifications of the lens, Aizenberg and her colleagues used a "bottom-up" technique, popular in nanotechnology development, in which successive layers of calcite are built up to make the lenses. The report makes effective use of the lead scientist's enthusiasm and engages it to ratchet up the excitement a notch, predicting nothing less than a revolution in manufacturing optical devices: "The new Bell Labs approach may revolutionize how crystals are made in the future for a wide variety of applications."

The themes of visualization, inscription devices, embodied sight, and biomimesis are no doubt sufficient stimuli to generate a Pavlovian response in a host of scholars who focus on questions of representation and related questions of epistemology, but the brittlestar's optical system is different in kind from the visualizing systems that many scholars in science studies and cultural studies are fond of reflecting on. What is at issue is not the geometrical optics model that positions language or representation as the lens that mediates between the object world and the mind of the knowing subject, a geometry of absolute exteriority between ontologically and epistemologically distinct kinds. The history of Western epistemology displays great diversity and ingenuity in generating different kinds of epistemological and

visualizing systems (Plato's is not Descartes's is not Kant's is not Merleau-Ponty's is not Foucault's), but as long as representation is the name of the game, the notion of mediation—whether through the lens of consciousness, language, culture, technology, or labor—holds nature at bay, beyond our grasp, generating and regenerating the philosophical problem of the possibility of human knowledge out of this metaphysical quarantining of the object world.[41]

The brittlestar is not a creature that thinks much of epistemological lenses or the geometrical optics of reflection: the brittlestar does not have a lens serving as the line of separation, the mediator between the mind of the knowing subject and the materiality of the outside world. Brittlestars don't *have* eyes; they *are* eyes. It is not merely the case that the brittlestar's visual system is embodied; its very being is a visualizing apparatus. The brittlestar is a living, breathing, metamorphosing optical system. For a brittlestar, being and knowing, materiality and intelligibility, substance and form, entail one another. Its morphology—its intertwined skeletal and diffuse nervous systems, its very structure and form—entails the visualizing system that it is. This is an animal without a brain. There is no *res cogitans* agonizing about the postulated gap (of its own making) between itself and *res extensa*. There is no optics of mediation, no noumena-phenomena distinction, no question of representation.

Brittlestars are not fixated on the illusion of the fixity of "their" bodily boundaries, and they wouldn't entertain the hypothesis of the immutability of matter for even a moment. Dynamics aren't merely matter in motion to a brittlestar when matter's dynamism is intrinsic to the brittlestar's biodynamic way of being. A brittlestar can change its coloration in response to the available light in its surroundings. When in danger of being captured by one predator or another, a brittlestar will break off the endangered body part (hence its name) and regrow it. The brittlestar is a visualizing system that is constantly changing its geometry and its topology—autonomizing and regenerating its optics in an ongoing reworking of its bodily boundaries.[42] Its *discursive practices*—the boundary-drawing practices by which it differentiates itself from the environment with which it intra-acts and by which it makes sense of its world, enabling it to discern a predator, for example—*are materiality enacted*.[43] The brittlestar's bodily structure is a material agent in what it sees and knows as part of the world's dynamic engagement in practices of knowing. Similarly, its bodily materiality is not a passive, blank surface awaiting the imprint of culture or history to give it meaning or open it to change; its very substance is morphologically active and generative and plays an agentive role in its differential production, its ongoing materialization. That is, *its differential materialization is discursive*—entailing causal practices reconfiguring boundaries and properties that matter to its very existence.[44] The ongoing reconfigurings of its bodily boundaries and connectivity are products of iterative causal intra-actions—material-discursive practices—through which the agential cut between "self" and "other" (e.g., "surrounding environment") is differentially enacted (e.g., in one agential cut, a given arm is part of the former; in another it is part of the latter). The ability to distinguish self from other, to track and dodge predators, for example, is requisite for the brittlestar's survival, but this does not imply that the categories need to be fixed; on the contrary, the brittlestar's survival depends on its capacity to discern the reality of its changing and relational nature. Intelligibility and materiality are not fixed aspects of the world but rather intertwined agential performances. This eye, this being, is a living optics topologically enfolding bits of the environment within itself and expelling parts of itself to the environment as part of its biodynamics. This apparatus serves both as the condition for the possibility of the intertwined practices of knowing and being and as a causally productive force in its further materializations. Talk about a multifunction biomaterial!

Brittlestars challenge not only disembodied epistemologies but also traditional, and indeed many nontraditional, notions of embodiment. Bodies are not situated *in* the world; they are part *of* the world.[45] Objectivity can't be a matter of seeing from somewhere, as opposed to the view from nowhere (objectivism) or everywhere (relativism), if being situated in the world means occupying particular coordinates in space and time, in culture and history. Just as the importance of the body as a performance rather than a thing can hardly be overemphasized, so should we resist the familiar conception of spacetime as a preexisting Euclidean container (or even a non-Euclidean manifold) that presents separately constituted bodies with a place to be or a space through which to travel. "Position" is neither an absolute nor an a priori determinate feature of space. The spacetime manifold does not sit still while bodies are made and remade. The relationship between space, time, and matter is much more intimate. Spacetime itself is iteratively reconfigured through the ongoing intra-activity of the world. The world is an ongoing intra-active engagement, and bodies are among the differential performances *of* the world's dynamic intra-activity, in an endless reconfiguring of boundaries and properties, including those of spacetime. Technoscientific and other practices entail space-time-matter-in-the-making. Nothing stands separately constituted and positioned inside a spacetime frame of

reference, nor does there exist a divine position for our viewing pleasure located outside the world.[46] There is no absolute inside or absolute outside. There is only exteriority within, that is, agential separability. *Embodiment is a matter not of being specifically situated in the world, but rather of being of the world in its dynamic specificity.*

Interestingly, some ophiuroids have bioluminescent arms that continue to wiggle and emit light after breaking off. Marine biologists understand this as an effective survival tactic that a brittlestar performs to distract predators while it escapes. Is this jettisoned limb simply a piece of an organic-inorganic structure shuttering with remnant reflex energy or a companion species helping out? If the detached limb's continuing movements are judged to be mere reflex on the basis that the fragment has no brain, what of the original organism that is a smart material without a brain, and a living contestation of the organic-inorganic binary? Brittlestar species exhibit great diversity in sexual behavior and reproduction: some species use broadcast spawning, others exhibit sexual dimorphism, some are hermaphroditic and self-fertilize, and some reproduce asexually by regenerating or cloning themselves out of the fragmented body parts. When is a broken-off limb only a piece of the environment, and when is it an offspring? At what point does the "disconnected" limb belong to the "environment" rather than the "brittlestar"? Is contiguity of body parts required in the specification of a single organism? Can we trust visual delineations to define bodily boundaries? Can we trust our eyes? Connectivity does not require physical contiguity. (Spatially separate particles in an *entangled state* do not have separate identities but rather are part of the same phenomena.)[47] Is the connection between an "offspring" regenerated from a fragmented body part and the parent brittlestar the same as its connection to a dead limb or the rest of the environment? Imagine the possibilities for lost limb memory trauma when it comes to brittlestars! Rethinking embodiment in this way will surely require rethinking psychoanalysis as well.

Brittlestars are living, breathing, mutating liminal diffraction gratings—they live at the edge of *being* diffraction gratings. Negotiating complex sets of changing relations concerning bodily boundaries, brittlestars are evolutionarily attuned to processes of differentiation. They simply cannot afford to ignore potential diffraction effects. Diffraction effects limit the ability of a lens (or system of lenses) to resolve an image. The greater the diffraction effects, the less determinate the boundaries of an image are, that is, the more the resolution is compromised. This is a fundamental physical limit (not merely a practical one).[48] Brittlestars have evolved in intra-action with their environment in just such a way that their microlenses are optimized to maximize visual acuity (for the discernment of predators, hiding places, and other important phenomena) in a creative tension, a trade-off, between the resolution of detail and diffraction effects.[49] How that tension is negotiated clearly matters: the possibilities for survival are at stake in the brittlestar's ability to differentiate bodily boundaries. *Diffraction is not about any difference but about which differences matter*. The brittlestar lives agential separability, the possibilities for differentiation without individuation.

Brittlestars know better than to get caught up in a geometrical optics of knowing. Clearly they are in a different genus from the mediating machines, inscription devices, lenses, panopticons, and various other epistemological tools that many scholars in science studies and cultural studies fancy. These approaches too often figure visualization as a matter of geometrical optics, leaving important factors of physical optics aside. But this will produce a fuzzy image at best. Limiting an analysis to the domain of geometrical optics, in the neglect of diffraction and other important physical optics effects, corresponds to limiting the analysis to the domain of classical physics in the neglect of quantum effects.[50] As we have seen, there are profound differences between classical and quantum physics—the epistemology and ontology that each entails are strikingly different. In a sense, this neglect of physical optics (quantum physics) can be understood as marking the epistemological limit of science studies. There is more to nature than "nature-as-the-object-of-human-knowledge."[51] The latter constitutes a re-veiling (which provokes the seeming need for a revealing) of nature, yet again. Boundary-making practices do not merely pick out the epistemic object, backgrounding the rest. And scientific practices are not merely practices of knowing, and the knowledge produced is not ours alone. Even in direct challenges to Western philosophy's traditional conceptions of epistemology, there is a tendency to continue to think of knowers as human subjects, albeit appropriately hooked into our favorite technological prostheses. In the absence of a vigorous examination of the ontological issues, the locus of knowledge is presumed to be never too far removed from the human, and so the democratizing move is to invite nonhuman entities into our sociality. But the nature-culture dualism is not undermined by inviting everything into one category (man's, yet again). The point of challenging traditional epistemologies is not merely to welcome females, slaves, children, animals, and other dispossessed Others (exiled from the land of knowers by Aristotle more than two millennia ago) into the fold of knowers but to better account for the ontology of knowing.

Brittlestars literally enact my agential realist ontoepistemological point about the entangled practices of knowing and being. They challenge our Cartesian habits of mind, breaking down the usual visual metaphors for knowing along with its optics of mediated sight. Knowledge making is *not* a mediated activity, despite the common refrain to the contrary. Knowing is a direct material engagement, a practice of intra-acting with the world as part of the world in its dynamic material configuring, its ongoing articulation. The entangled practices of knowing and being are material practices. The world is not merely an idea that exists in the human mind. To the contrary, "mind" is a specific material configuration of the world, not necessarily coincident with a brain. Brain cells are not the only ones that hold memories, respond to stimuli, or think thoughts.[52] Brittlestars intra-act with their ocean environment and respond to differential stimuli made intelligible through these intra-actions, adjusting their positions and reworking their bodies in order to avoid predators or find food or shelter, all without brains or eyes. (Was the cell biologist Daniel Mazia being merely metaphorical when he remarked that "the gift of the great microscopist is the ability to think with the eyes and see with the brain"? Surely a plethora of statements about tacit knowing, including a wealth of testimonials offered by scientists, suggests some more literal, material meaning.)

"I think, therefore I am" is not the brittlestar's credo. Knowing is not a capacity that is the exclusive birthright of the human. The "knower" cannot be assumed to be a self-contained rational human subject, nor even its prosthetically enhanced variant. There is no res cogitans that inhabits a given body with inherent boundaries differentiating self and other. Rather, subjects are differentially constituted through specific intra-actions. The subjects so constituted may range across some of the presumed boundaries (such as those between human and nonhuman and self and other) that get taken for granted. Knowing is a distributed practice that includes the larger material arrangement. To the extent that humans participate in scientific or other practices of knowing, they do so as part of the larger material configuration of the world and its ongoing open-ended articulation.

Knowing is a specific engagement of the world where part of the world becomes differentially intelligible to another part of the world in its differential accountability to and for that of which it is a part. In traditional humanist accounts, intelligibility requires an intellective agent (that to which something is intelligible), and intellection is framed as a specifically human capacity. But in my agential realist account, intelligibility is an ontological performance of the world in its ongoing articulation. It is not a human-dependent characteristic but a feature of the world in its differential becoming. The world articulates itself differently. And knowing does not require intellection in the humanist sense, either; knowing is a matter of differential responsiveness (as performatively articulated and accountable) to what matters.

Crucially, knowing is not a matter of mere differential responsiveness in the sense of simply having different responses to different stimuli. Knowing requires differential accountability to what matters and is excluded from mattering. That is, what is required is differential responsiveness that is accountable to marks on bodies as part of a topologically dynamic complex of performances. As Rouse remarks, "There is nothing about the letters p-o-s-i-t-i-o-n or the po-'zi-shun that magically . . . connects them to what is disclosed in measurements using [an] apparatus with internally fixed parts; only their actual ongoing use in such circumstances, in reliably recognizable and normatively accountable ways, can account for their discursive significance" (Rouse 2004, 153). But recognition need not entail cognition in humanist terms. A brittlestar can recognize a predator and successfully negotiate its environment to elude capture despite the fact that it has no brain. A brittlestar is not some ideal Cartesian subject, but through specific practices of intra-active engagement, it differentially responds (not simply in the sense of responding differently to different things that are out there but) in ways that matter. There are stakes—life-and-death stakes—in getting it wrong.[53] Furthermore, "recognizability" is not a fixed and universal notion but obtains its meaning through its ongoing use in specific practices. What is at issue, then, is not mere differential responsiveness but normative differential responsiveness. Different material intra-actions produce different materializations of the world, and hence there are specific stakes in how responsiveness is enacted. In an important sense, it matters to the world how the world comes to matter.

Brittlestars are not merely tools that we can use to teach us about biomimesis and enhanced communication networks. Brittlestars are living testimony to the inseparability of knowing, being, and doing. On the one hand, we trust our eyes when it comes to believing that boundaries that we see are sharp inherent edges marking the limits of separate entities, even though upon closer examination the diffraction effects—the indefinite nature of those boundaries—become clear (which is not to suggest that there really are no boundaries or that what is at stake is a postmodern celebration of the blurring of boundaries; we have learned too much about diffraction to think in these simplistic terms). On the other hand, we don't trust our eyes to give us reliable access to the material world; as inheritors of the Cartesian legacy, we would rather put our faith in representations instead of matter, believing that we have a kind of direct access to the content of our representations that we lack toward that which is represented. To embrace representationalism and its geometry or geometrical optics of externality is not merely to make a justifiable approximation that can be fixed by adding further factors or perturbations at some later stage, but rather to start with the wrong optics, the wrong ground state, the wrong set of epistemological and ontological assumptions. Haraway's move away from her earlier "an optics is a politics of positioning" to her later "diffraction is an optical metaphor for the effort to make a difference in the world" signals the kind of shift that is required (Haraway 1991, 193; 1997, 16).

There is more to diffraction than meets the eye. As we have learned from our quantum mechanical studies of diffraction, it is a much more subtle and profound phenomenon than the classical understanding suggests. The phenomenon of diffraction does not merely signify the disruption of representationalism and its metaphors of reflection in the endless play of images and its anxieties about copy and original and displacements of the Same elsewhere. Diffraction is an ethico-onto-epistemological matter. We are not merely differently situated in the world; "each of us" is part of the intra-active ongoing articulation of the world in its differential mattering. Diffraction is a material-discursive phenomenon that challenges the presumed inherent separability of subject and object, nature and culture, fact and value, human and nonhuman, organic and inorganic, epistemology and ontology, materiality and discursivity. Diffraction marks the limits of the determinacy and permanency of boundaries. One of the crucial lessons we have learned is that agential cuts cut things together and apart. *Diffraction is a matter of differential entanglements. Diffraction is not merely about differences, and certainly not differences in any absolute sense, but about the entangled nature of differences that matter.* This is the deep significance of a diffraction pattern.[54] *Diffraction is a material practice for making a difference, for topologically reconfiguring connections.*

Brittlestars are not pure bits of nature or blank slates for the imprinting of culture. They are not mere resources or tools for human interventions. They are not simply superior optical engineers or natural inspirations for the enterprising ingenuity of humans. Brittlestars are phenomena intra-actively produced and entangled with other phenomena. They are agentive beings, lively configurations of the world, with more entanglements than arms. They are not merely objects of our knowledge-making and product-making projects. "Humans" and "brittlestars" learn about and co-constitute each other through a variety of brittlestar-human intra-actions. Biomimesis may be the goal of certain research projects that seek to appropriate the ingenuity of the brittlestar's lens system, but this practice cannot be understood as a process of copying the other. Nature is not a pure essence that exists "out there" or on a slide positioned under the objectives of our microscopes. In the game of geometrical optics would the brittlestar be the lens that we look at, or through, or with? Brittlestars are not gripped by the idea of mirroring, imitation, reflection, or other modes of the tropology of Sameness. These echinoderms don't reflect on the world; they are engaged in making a difference in the world as part of the world in its differential becoming, and so are we. The specific nature of our intra-actions with brittlestars matters. For all we have learned from our intra-actions with brittlestars, the issue is not whether or not we are willing to follow Nature's example. The attending ethico-onto-epistemological questions have to do with responsibility and accountability for the entanglements "we" help enact and what kinds of commitments "we" are willing to take on, including commitments to "ourselves" and who "we" may become.

It would be a serious error to mistake biomimesis for mere imitation. The emerging field of biomimetics is not about copies of originals or even copies of copies without beginning or end. On the contrary, biomimesis is a particularly poignant call for the incorporation of difference at every level in breaking the deadening and sinister symmetry of Sameness that uses the hall of mirrors to suck time, history, and matter into the black hole of stasis (leaving in its stead a culture of no culture and a nature of no nature).[55] The biomimetic-inspired study of the brittlestar reveals the limitations of the geometrical optics of mirroring and shows us that the crucial point is not mirroring but its creative undoing, not sameness reproduced without end but attentiveness to differences that matter. Contemporary practitioners of biomimesis do not claim to be making replicas of nature; rather, they are engaged in practices that use nature as inspiration for new engineering designs. Biomimetics honors Mother Nature as the primo engineer, but it doesn't promise to abide by her methods. It embraces new innovations, new materials, new techniques, new applications. Bringing the new to light is its highest principle. Of course, the new bio-info-nano-technologies embrace the new for very practical reasons: aside from the excitement and romantic overtones that inevitably accompany the story of the scientist as explorer breaking into new frontiers, and its obvious advertising benefits, without the new there is simply no copyright to be gained.

There's an important point to be made about the new in light of the entangled nature of spacetimematterings. As Hans-Jörg Rheinberger points out the new isn't the new until it is already not new—for the new "becomes a novelty only in a transformation which makes it a trace of something to which it has given rise" (1997, 177). Originals don't preexist as such and mimesis can't be the reproduction of what came before, not when time itself is constituted through the dynamics of intra-activity and the past remains open to material reconfigurings (see chapter 7). As we saw in chapter 7, the historiality of phenomena is written into their materialization, their bodily materiality holds the memories of the traces of its enfoldings; space and time (like matter) are phenomenal, that is, they are intra-actively produced in the making of phenomena; neither space nor time exist as determinate givens outside of phenomena. As a result of the iterative nature of intra-active practices that constitute phenomena, the "past" and the "future" are iteratively reconfigured and enfolded through one another: phenomena cannot be located in space and time; rather, phenomena are material entanglements that "extend" across different spaces and times. The production of the new can't be located and it certainly can't be owned. Neither the past nor the future is ever closed. It's not that the new is generated in time; rather, what is at issue is the intra-active generation of new temporalities, new possibilities, where the "new" is the trace of what is yet to come.[56] © is not a symbol of ownership of the right to copy, but rather of the responsibilities entailed in producing differences (for whom and at what costs?).[57]

Biomimetics is a nodal point around which nanotechnologies, biotechnologies, and infotechnologies are becoming more and more complexly entangled. This accounts for a great deal of the current fascination with biomimetics, the enthusiastic support it is receiving from government agencies, universities, and private industry, and the rapid growth of research centers that are fashioned on a model of hybridity (drawing together interdisciplinary, international, and interorganization teams) that cultural studies, women's studies, ethnic studies, and other critical social studies programs have been touting the advantages of for decades, but with little real structural or material support from the colleges and universities that claim to pride themselves on the interdisciplinary efforts that spur them on to the cutting edge of education and research.[58] As we entertain the possibilities for forming partnerships with brittlestars and other organisms for biomimetic projects, we are co-constituting ourselves into assemblages that "mimic" (but do not replicate) the entanglements of the objects we study and the tools that we make. The entanglements we are a part of reconfigure our beings, our psyches, our imaginations, our institutions, our societies; "we" are an inextricable part of what gets reworked in our R&D projects. The ethical questions that we will want to consider are not only about how nonhuman animals are being appropriated for human desires but also about how our desires and our beings are co-constitutively reconfigured as well.

One very important lesson we have gained from our intra-actions with brittlestars (where the objective referent here is the phenomenon, not some allegedly pure bit of nature) is that ethics is not simply about the subsequent consequences of our ways of interacting with the world, as if effect followed cause in a linear chain of events. Ethics is about mattering, about taking account of the entangled materializations of which we are a part, including new configurations, new subjectivities, new possibilities—even the smallest cuts matter. Biomimesis is not about making copies but about enacting new cuts and reconfiguring entanglements. We are much more intimately connected than the notion of mimesis connotes. We don't have the distances of space, time, and matter required to replicate "what is"; in an important sense, we are already materially entangled across space and time with the diffractive apparatuses that iteratively rework the "objects" that "we" study. The ethical practice of biomimesis will require specific case-by-case accountings for marks on bodies. Technoscientific practices are about making different worldly entanglements, and ethics is about accounting for our part of the entangled webs we weave.

ENTANGLED GENEALOGIES

> The ultra-fast computers of the future will be based on beams of light that exploit the strange properties of the sub-atomic or quantum mechanical world. Using light and quantum mechanics offers the prospect of computers trillions of times more powerful than we have today. The first, tentative but encouraging, steps have been made towards primitive quantum computers.
>
> —DAVID WHITEHOUSE, "Q&A: Teleportation," *BBC News*, June 14, 2004

> New paradigms will use advances in quantum computation and molecular and nano-electronics to devise radically faster computers to solve problems previously described as "uncomputable," such as full-scale simulations of our biosphere or surgical simulations. Viewing cells as computational devices will help enable the design of next generation computers that feature self organization, self repair, and adaptive characteristics that we see in biological systems.
>
> —NSF TESTIMONY TO CONGRESS, March 1, 2000

Testifying before Congress, a National Science Foundation officer explains "quantum entanglement" to our government representatives: "Two particles can have linked spins even though they are at a distance [and appear to be completely separate entities]. Manipulating one particle and then reading the spin of the other, linked, particle is the basis of quantum information teleportation."[59] Is this the late-night hallucination of a physics student cramming for an exam? A skit on *Saturday Night Live*? Or a national news report on yet another incident of wasted government spending slotted for the "Fleecing of America" segment? Surprisingly, the answer is none of the above. This statement on quantum entanglement is from actual testimony, important testimony regarding research funded by a host of government agencies. As discussed in chapter 7, quantum entanglement—which challenges the presumed ontological separability of seemingly individual particles—is a phenomenon that lies at the heart of quantum physics. But why are the National Security Agency (NSA), the Defense Advanced Research Projects Agency (DARPA), the National Reconnaissance Office (NRO), and other U.S. federal agencies including the Army, Navy, and Air Force, the Advanced Research and Development Agency (ARDA), the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology (NIST), and the Department of Energy (DOE) interested in quantum entanglement?[60]

For decades, questions about the meaning and implications of quantum theory, foundational issues that cut to the very core of our understanding of the theory's nature, were considered "merely philosophical," that is, of no practical import. The impassioned debate between Bohr and Einstein belonged to the dustbin of history, and students who wanted to know something more about quantum theory than how to use it as a tool for doing calculations were directed, with an obligatorily pejorative tone, to seek counsel in the philosophy department, where questions of whether trees that fall in forests in the absence of listening subjects still make noises would not fall on deaf ears. The implication was that if one was seriously interested in the meta-physical issues, one could, and indeed one should, leave the serious endeavor of physics and pick up a career in history or philosophy of science. There were a few exceptions; a scant number of researchers in the field of the foundations of quantum mechanics were hired in physics departments or already had tenure in physics departments, but by and large the physics community just wasn't interested. In the past decade or so, things have changed. Now, all of a sudden, "metaphysical" issues have surfaced as a topic in physics, sparking the interest not only of physicists but also of a host of government officials, computer scientists, international bankers, and entrepreneurs around the world.[61] We have entered what the National Academy of Sciences calls the "Second Quantum Revolution."

The basis for the new quantum revolution is quantum entanglement, an idea that has been around since the mid-1930s but has only very recently been acknowledged as the very essence of quantum physics. Unlike the original quantum revolution, the new one is not so much a revolution in ideas (at least it is not widely acknowledged as such) but a revolution in technological potential. In the 1990s, physicists began to take quantum entanglement seriously as they realized its extraordinary potential as the basis for new technological endeavors including quantum computing, quantum cryptography, and quantum teleportation. Let's take a brief look at each of these innovations.[62]

Quantum computers are touted as a major contender for increased computing power in the postsilicon era. They have the potential to accelerate computations and solve problems that have heretofore been resistant to solution, including the factoring of large integers, the acceleration of combinatorial searches, and the simulation of complex physical systems. This anticipated "quantum leap" in computing power is due to quantum computers' intrinsic massive "parallelism," which enables them to perform many operations simultaneously.[63] The point was made to the U.S. congressional representatives in this way:

> Since the invention of the silicon integrated circuit in 1961 to the present, the number of devices that can be placed on a single silicon chip has roughly doubled every 12 to 18 months. This means that every ten years, the number of devices on chips increases about a thousand-fold. This is done by shrinking device sizes and is achieved by constant improvements in chemistry, photolithography, clean rooms, and other efforts. This doubling rate is known as Moore's law. For the computing industry, the shrinking devices and increasing density [have] enabled the information technology revolution through staggering increases in speed and functionality of computers accompanied by astonishing decreases in costs. We know that this cannot continue for long—the size of atoms is a very hard limit and very close in time. . . . If we are to continue to see improvements in the performance and cost of computing, we must go beyond silicon.

Quantum computing represents an important possibility for maintaining our competitive edge.

But quantum computing promises more than additional computing

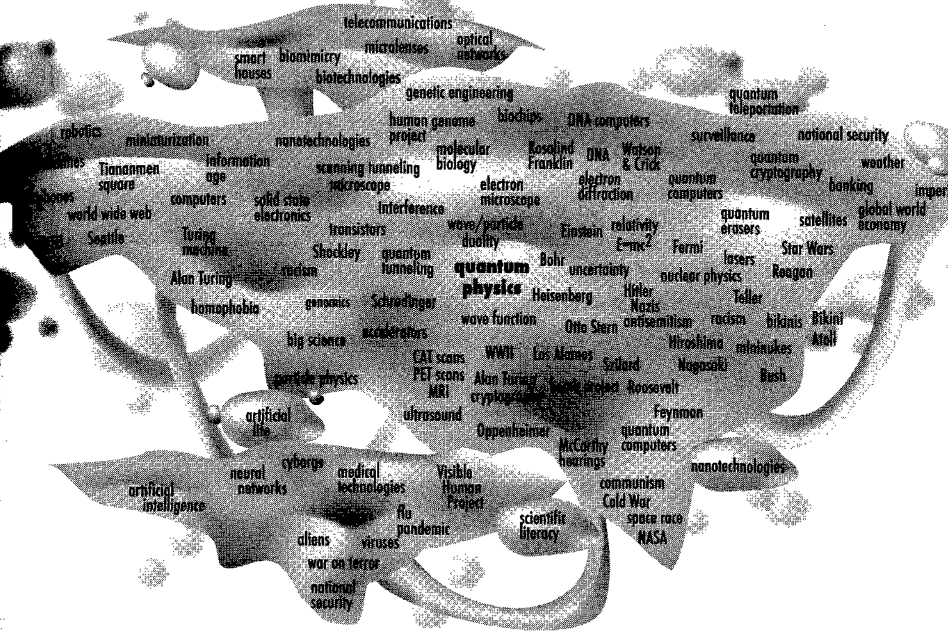
power, for the project is entangled with issues that cut to the heart of national security and control of global information systems. Though it may seem as if the factoring of large integers would be of interest only to a group of mathematicians who revel in the innocent pleasures of playing with numbers, factoring is the basis of encryption systems that seek to keep banking transactions secure. In theory, a powerful-enough quantum computer could pose a threat to the international banking system as well as to national security. Perhaps it isn't surprising, then, that overall support for Quantum Information Science (QIS) in the United States has risen from about $1 million in fiscal year 1995 to over $30 million in fiscal year 2000.[64] In fact there has been an explosion of such efforts throughout the so-called first world. Currently, "quantum computers are the focus of a mammoth research effort by a consortium including several universities in Australia and the U.S., as well as Los Alamos, leading those in the field to dub it the 'Manhattan Project of quantum computing.' "[65]

Quantum cryptography is an emerging technology that promises the secure transmission of information between distant locations (e.g., between two satellites). Significantly, the security of quantum crytpographic transmissions is guaranteed by the laws of quantum mechanics such that not only would any attempt to tap such a transmission fail, but no attempt would be able to evade detection. While quantum computing may take decades to realize, quantum cryptography is already commercially available:

> Long before [a time when quantum computing may be realized], moreover, entanglement and superposition may find practical application in other technologies. For example, quantum cryptography has the potential to exchange information with guaranteed secrecy; commercial products already exist. Quantum entanglement may also permit more accurate and better synchronized atomic clocks, which in turn could improve GPS systems and mobile communications networks.
>
> And of course, that is just the beginning. Attempts to tame the quantum realm are also opening up new possibilities for nanoscience and other areas of physics, and are certain to lead to technologies that today's physicists cannot even fathom.[66]

A third research area is quantum teleportation. Although it may not lead anytime soon (if ever) to the realization of a *Star Trek*–style transporter that makes an object dematerialize in one place and rematerialize in another (or at least its replica), quantum teleportation is a method by which physicists can transport the properties of one object to another even if the objects are on opposite sides of the galaxy (at least in principle). Even if scientists do find a way to handle the vast information that is a human being, the prospect of teleporting beings is rather grim, for, as Charles Bennett and his colleagues have shown, it means destroying the original and replacing it with a replica (Bennett et al. 1993). The teleportation of quantum information has been realized in the laboratory, and though it won't replace air travel in the near future, it will most likely have uses in quantum computing and quantum cryptography. No wonder quantum entanglement has gotten more people's attention than a few metaphysicians and a small group of die-hard physicists and philosophers intent on figuring out the deep mysteries of the quantum theory.[67]

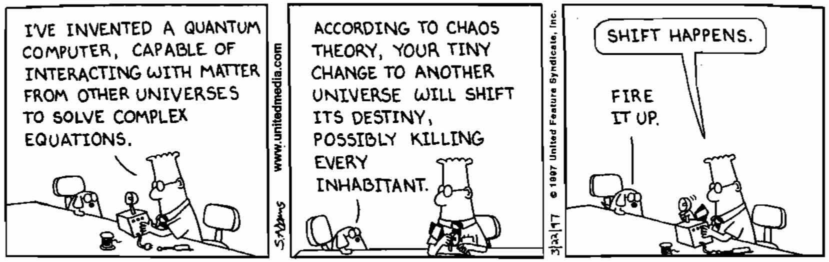
Quantum physics is part of a complexly entangled web of phenomena that include scientific, technological, military, economic, medical, political, social, and cultural apparatuses of bodily production, to name but a few. Figure 34 shows an illustration that attempts to offer some sense of this complex and lively manifold of entangled and changing practices and possibilities. The illustration is wholly inadequate, impressionistic at best, but hopefully of some use for the reader who shares my yearning and struggles to see, feel, touch, taste, smell, hear, and otherwise sense phenomena with the mind's eye (and it's not only the last word in this sentence that strives to give some sense of this material practice of grasping phenomena that ought to be put in scare quotes; of course, "grasping" is a material-discursive practice that intra-acts rather than interacts with its object). For one thing, the complex manifold of connections in question is an ever-changing multidimensional topological manifold *of* spacetimematter, not a three-dimensional object (assuming you'll grant that) located in space with the barest hint of time thrown in for good measure, that not only comes across as spatialized but is literally represented spatially (by the perhaps all-too-subtle suggestion that some "blobs" are in the process of materializing while others are becoming less substantial). The wormholes, the array of handles connecting nonproximate points that (only) seem distant or disconnected, barely hint at a much denser and more complex set of entanglements that could not be placed on the diagram without obscuring the image. Furthermore, the illustration fails to convey the dynamic set of changing relations and multiple en/foldings that are part of its ongoing reconfiguring. How to represent not merely the limits of representationalism (in the tradition of Velázquez or Magritte, for example) but the agential realist notions of causality and agency that are entailed in entanglements is a question that one simply can't wrap one's mind around (by definition). In particular, the notion of entanglement needs to be under-



34 Entangled genealogies. *Illustration by Nicolle Rager Fuller and Karen Barad.*

stood in terms of the relational ontology of agential realism. While the illustration gives the impression that the manifold is an assemblage of individual events, entities, and sets of practices, but the fact is that these apparatuses of bodily production are intra-acting with and mutually constituting one another; that is, what is at issue is the primacy of relations over relata and the intra-active emergence of "cause" and "effect" as enacted by the agential practices that cut things together and apart. All in all, perhaps at best the illustration conveys some sense of the multiplicity of apparatuses that are part of these entangled genealogies, but even at that the labels don't do justice to the nature of these different and differently connected changing materialities. Or maybe all that it is able to hint at is some sense of the need to read genealogies for their constitutive exclusions. But then again, representations are not (more or less faithful) pictures of what is, but productive evocations, provocations, and generative material articulations or reconfigurings of what is and what is possible.

Recall that apparatuses are themselves phenomena—the result of intra-actions of material-discursive practices—and the enfolding of phenomena



35 Shift happens. *From Dilbert, © Scott Adams, dist. by United Feature Syndicate, Inc.*

into subsequent iterations of particular practices (which may be traded and mutated across space, time, and subcultures, in the iterative reconfiguring of spacetimematter itself) constitutes important shifts in the nature of the intra-actions that result in the production of new phenomena, and so on. Which shifts occur matter for epistemological as well as ontological reasons: a different material-discursive apparatus of bodily production materializes a different configuration of the world, not merely a different description of a fixed and independent reality. We are responsible for the world of which we are a part, not because it is an arbitrary construction of our choosing but because reality is sedimented out of particular practices that we have a role in shaping and through which we are shaped. (The Dilbert cartoon in figure 35 offers a different illustration, a different way of conveying the crucial point that in our entangled engagements with and as part of the universe each shift matters.)

What we need is an understanding of the material-discursive practices by which these connections are formed and reformed, not in space and time but in the very configuring and reconfiguring of spacetimematter. In particular, the responsible practice of science requires a full genealogical accounting of the entangled apparatuses or practices that produce particular phenomena.[68] In contrast to more traditional conceptions of objectivity, which are only responsible to the norms of correct practice as narrowly conceived (e.g., the correct operation of equipment, the production of determinate marks on bodies, the following of standards of interpretation to produce intelligible results, the following of correct procedures for reporting results), objectivity in an agential realist sense requires a full accounting of the larger material arrangement (i.e., the full set of practices) that is a part of the phenomenon investigated or produced. (To do otherwise is to misidentify

the objective referent.) Hence objectivity requires an accounting of the constitutive practices in the fullness of their materialities, including the enactment of boundaries and exclusions, the production of phenomena in their sedimenting historiality, and the ongoing reconfiguring of the space of possibilities for future enactments. The point is that more is at stake than "the results"; intra-actions reconfigure both what will be and what will be possible—they change the very possibilities for change and the nature of change. Learning how to intra-act responsibly as part of the world means understanding that "we" are not the only active beings—though this is never justification for deflecting our responsibility onto others.[69]

TOWARD AN ETHICS OF MATTERING

> Proximity, difference which is non-indifference, is responsibility.
>
> —EMMANUEL LEVINAS, *Otherwise than Being, or Beyond Essence*

For Emmanuel Levinas, responsibility is not a relation between two subjects; rather, the otherness of the Other is given in responsibility. "Responsibility is "the essential, primary and fundamental mode of subjectivity. . . . Ethics . . . does not supplement a preceding existential base; the very node of the subjective is knotted in ethics understood as responsibility" (Levinas 1985, 95). Ethics grounds human experience (not the other way around).

Levinas rejects the metaphysics of the self that serves as a foundation for conventional approaches to ethics. Subjectivity is not a matter of individuality but a relation of responsibility to the other. Crucially, then, the ethical subject is not the disembodied rational subject of traditional ethics but rather an embodied sensibility, which responds to its proximal relationship to the other through a mode of wonderment that is antecedent to consciousness. As the feminist theorist Ewa Plonowska Ziarek explains, the "ethical significance of the body is crystallized in the figure of touch and sensibility, in 'the quite simple attempt to touch the other, to feel the other' " (Ziarek 2001, 56). Ziarek emphasizes that, for Levinas, embodiment is neither a passive surface for the inscription of culture nor the biological body:

> Levinas rethinks embodiment not only as the condition of relations to objects but also as a prototype of an ethical experience. In contrast to the transcendence of the body in self-reflection, "oneself," or ipseity, signifies for Levinas an embodied self—a prelogical, presynthetic entwinement of thought and carnality, or what Levinas calls "being in one's skin." (49–50)

Being in one's skin means that one cannot escape responsibility: the prior ethical relation of "having-the-other-in-one's-skin" conditions the constriction of embodiment, which "does not unify the ego but, on the contrary, inscribes the noncoincidence with oneself within the lived body and makes it the basis of the ethical relations to others" (55). Before all reciprocity in the face of the other, I am responsible.

But if responsibility is not a commitment that a subject chooses but rather an incarnate relation that precedes the intentionality of consciousness, "an obligation which is *anachronistically* prior to every engagement," then it seems we cannot ignore the full set of possibilities of alterity—that "having-the-other-in-one's-skin" includes a spectrum of possibilities, including the "other than human" as well as the "human." And if ethical relations extend to the other-than-human, then the "noncoincidence with oneself" is clearly not a singular feature of human embodiment. Responsibility—the ability to respond to the other—cannot be restricted to human-human encounters when the very boundaries and constitution of the "human" are continually being reconfigured and "our" role in these and other reconfigurings is precisely what "we" have to face. A humanist ethics won't suffice when the "face" of the other that is "looking" back at me is all eyes, or has no eyes, or is otherwise unrecognizable in human terms. What is needed is a posthumanist ethics, an ethics of worlding.

Levinas argues that "culture does not come along and add extra axiological attributes, which are already secondary and grounded, onto a prior, grounding representation of the thing. The cultural is essentially embodied thought expressing itself, the very life of flesh manifesting" (quoted in Ziarek 2001, 53). What would it mean to acknowledge that this is true of nature as well (as culture)—that nature expresses itself, that nature is not the other of thought or speech?[70] What if we were to acknowledge that the nature of materiality itself, not merely the materiality of human embodiment, always already entails "an exposure to the Other"? What if we were to recognize that responsibility is "the essential, primary and fundamental mode" of objectivity as well as subjectivity?

In my agential realist account, matter is a dynamic expression/articulation of the world in its intra-active becoming. *All* bodies, including but not limited to human bodies, come to matter through the world's iterative intra-activity—its performativity. Boundaries, properties, and meanings are differentially enacted through the intra-activity of mattering. Differentiating is not about radical exteriority but rather agential separability. That is, differentiating is not about othering or separating but on the contrary about making connections and commitments. The very nature of materiality is an entanglement. Matter itself is always already open to, or rather entangled with, the "Other." The intra-actively emergent "parts" of phenomena are co-constituted. Not only subjects but also objects are permeated through and through with their entangled kin; the other is not just in one's skin, but in one's bones, in one's belly, in one's heart, in one's nucleus, in one's past and future. This is as true for electrons as it is for brittlestars as it is for the differentially constituted human. (Electrons, like brittlestars, are complex phenomena that are lively and enlivened; memory and re-member-ing are not mind-based capacities but marked historialities ingrained in the body's becoming.) Just as the human subject is not the locus of knowing, neither is it the locus of ethicality. We (but not only "we humans") are always already responsible to the others with whom or which we are entangled, not through conscious intent but through the various ontological entanglements that materiality entails. What is on the other side of the agential cut is not separate from us—agential separability is not individuation. Ethics is therefore not about right response to a radically exterior/ized other, but about responsibility and accountability for the lively relationalities of becoming of which we are a part.

Rejecting the metaphysics of individualism that serves as a foundation for traditional approaches to ethics, agential realism proposes an alternative meta/physics that entails a reworking of the notions of causality and agency. Traditional conceptions of causation are concerned with the causal relationship between distinct sequential events. In my agential realist account, causality is rethought in terms of intra-activity. Intra-actions do not simply transmit a vector of influence among separate events. It is through specific intra-actions that a causal structure is enacted. Intra-actions effect what's real and what's possible, as some things come to matter and others are excluded, as possibilities are opened up and others are foreclosed. And intra-actions effect the rich topology of connective causal relations that are iteratively performed and reconfigured. This is a reworking of causality that not only goes beyond its classical conception but also goes beyond that of complex systems theory as well: "emergence," in an agential realist account, is dependent not merely on the nonlinearity of relations but on their intra-active nature (i.e., on nonseparability and nontrivial topological dynamics as well). Events and things do not occupy particular positions in space and time; rather, space, time, and matter are iteratively produced and performed. Traditional conceptions of dynamics as a matter of how the values of an object's properties change over time as the result of the action of external forces won't do. The very nature and possibilities for change are reworked.

With each intra-action, the manifold of entangled relations is reconfigured. And so consequentiality, responsibility, and accountability take on entirely new valences. There are no singular causes. And there are no individual agents of change. Responsibility is not ours alone. And yet our responsibility is greater than it would be if it were ours alone. Responsibility entails an ongoing responsiveness to the entanglements of self and other, here and there, now and then. If, as Levinas suggests, "proximity, difference which is non-indifference, is responsibility," then entanglements bring us face to face with the fact that what seems far off in space and time may be as close or closer than the pulse of here and now that appears to beat from a center that lies beneath the skin. The past is never finished once and for all and out of sight may be out of touch but not necessarily out of reach.[71] Intra-active practices of engagement not only make the world intelligible in specific ways but also foreclose other patterns of mattering. We are accountable for and to not only specific patterns of marks on bodies—that is, the differential patterns of mattering of the world of which we are a part—but also the exclusions that we participate in enacting. Therefore accountability and responsibility must be thought in terms of what matters and what is excluded from mattering.

The point is not merely that there is a web of causal relations that we are implicated in and that there are consequences to our actions. We are a much more intimate part of the universe than any such statement implies. If what is implied by "consequences" is a chain of events that follow one upon the next, the effects of our actions rippling outward from their point of origin well after a given action is completed, then to say that there are consequences to our actions is to miss the full extent of the interconnectedness of being. Future moments don't follow present ones like beads on a string. Effect does not follow cause hand over fist, transferring the momentum of our actions from one individual to the next like the balls on a billiards table. There is no discrete "I" that precedes its actions. Our (intra)actions matter—each one reconfigures the world in its becoming—and yet they never leave us; they are sedimented into our becoming, they become us. And yet even in our becoming there is no "I" separate from the intra-active becoming of the world. Causality is an entangled affair: it is a matter of cutting things together and apart (within and as part of phenomena). It is not about momentum transfer among individual events or beings. The future is not the end point of a set of branching chain reactions; it is a cascade experiment.

In his autobiography *Disturbing the Universe*, the physicist Freeman Dyson takes up the haunting question of J. Alfred Prufrock—"Do I dare disturb the universe?" T. S. Eliot's protagonist holds the question at arm's length, afraid of what it might mean to give it voice. Caught in inaction, indulging instead in endless reflection, mirrors upon mirrors, he watches his life from a distance, afraid to face all but the most petty self-conscious instances: "Shall I part my hair behind? Do I dare to eat a peach?" On the other hand, Dyson grabs hold of the question and considers it in relation to matters on the grandest scales and potentially of the gravest consequences. "Do I dare work on the hydrogen bomb?" is an inversion of "Do I dare eat a peach?" Prufrock's extreme self-consciousness—his compulsive indulgence in interminable reflections designed to keep himself inside his own head, endless worries upon endless worries stacked up like dirty dishes crafted as a distraction, a prophylactic against facing the really difficult questions in life—does not amount to responsible reflection about the consequences of the choices life holds. On the contrary, it adds up to nothing more than his pitiable inability to be in his life, to sing his love song to the universe. By contrast, Dyson's life is filled with decisions and actions that are deeply consequential. Dyson knows that the very survival of humankind may rest on some of the decisions he faces. He confronts the really tough questions, questions of life and death, and his reflections are subtle and informed. Ethics and science go hand in hand for this self-reflexive scientist (who—rather paradoxically, it seems—never met a technological project he couldn't find justification for working on). Dyson puts his moral stances on the table: his firm belief that "knowledge implies responsibility," his insistence that "it makes no sense to separate science from technology, technology from ethics, or ethics from religion," his realization while working on the design of a nuclear bomb at Livermore that "it is not possible to make a clean separation between peaceful and warlike bombs, or between peaceful and warlike motives," his belief in an ultimate "covenant between nature and man," even his dream about finally meeting his maker, which reveals the ultimate secret that we hold the future in our own hands. And yet, despite all his thoughtful considerations, Dyson's ethical questioning remains eerily faithful to the logic of Prufrock's question. The image is inverted, but the mirror remains in fact. The structure that separates reflections from actions and observer from observed is left in place.

"Do I dare disturb the universe?" What can such a question mean? Shall we stand outside the universe and just let it "run"? Shall we take the side of Newton or Leibniz in the debate about whether the clockwork must be rewound periodically or whether it will continue in a satisfactory fashion without intervention? How best to design a clockwork? What position is this to occupy? Can we assume the position of the perfect modest witness and merely observe the universe without disturbing it? When faced with an ethical choice about working on a new technological or scientific project, can we get that kind of distance? Enough to detach ourselves from responsibility? Can we simply follow our passion to know without getting our hands dirty? Or if we cannot stand back, and we find ourselves needing to intervene now and again to keep things in alignment or make an adjustment here or there, if we honor our responsibility by helping to shape the future, what kind of distance shall we presume is the right amount to get a good perspective on things? How many light-years away do we need to stand to make wise choices? Shall we use the universe as a toy model, tweak a few things, and see what happens?

What fantasy of distance is this? What notion of responsibility is presumed? "Do I dare disturb the universe?" is not a meaningful question, let alone a starting point for ethical considerations. Disturbance is not the issue, and "dare" is a perverse provocation. There is no such exterior position where the contemplation of this possibility makes any sense. We are *of* the universe—there is no inside, no outside. There is only intra-acting from within and as part of the world in its becoming.

A delicate tissue of ethicality runs through the marrow of being. There is no getting away from ethics—mattering is an integral part of the ontology of the world in its dynamic presencing. Not even a moment exists on its own. "This" and "that," "here" and "now," don't preexist what happens but come alive with each meeting. The world and its possibilities for becoming are remade with each moment. If we hold on to the belief that the world is made of individual entities, it is hard to see how even our best, most well-intentioned calculations for right action can avoid tearing holes in the delicate tissue structure of entanglements that the lifeblood of the world runs through. Intra-acting responsibly as part of the world means taking account of the entangled phenomena that are intrinsic to the world's vitality and being responsive to the possibilities that might help us and it flourish. Meeting each moment, being alive to the possibilities of becoming, is an ethical call, an invitation that is written into the very matter of all being and becoming. We need to meet the universe halfway, to take responsibility for the role that we play in the world's differential becoming.

APPENDIX A

Cascade Experiment

ALICE FULTON

Because faith creates its verification
and reaching you will be no harder than believing
in a planet's caul of plasma,
or interacting with a comet
in its perihelion passage, no harder
than considering what sparking of the vacuum, cosmological
impromptu flung me here, a paraphrase, perhaps,
for some denser, more difficult being,
a subsidiary instance, easier to grasp
than the span I foreshadow, of which I am a variable,
my stance is passional towards the universe and you.

Because faith in fact can help create those facts,
the way electrons exist only when they're measured,
or shy people stand alone at parties,
attract no one, then go home and feel more shy,
I begin by supposing our attrition's no quicker
than a star's, that like electrons
vanishing on one side
of a wall and appearing on the other
without leaving any holes or being
somewhere in between, the soul's decoupling
is an oscillation so inward nothing outward
as the eye can see it.
The childhood catechisms all had heaven,
an excitation of mist.
Grown, I thought a vacancy awaited me.
Now I find myself discarding and enlarging
both these views, an infidel of amplitude.

Because truths we don't suspect have a hard time
making themselves felt, as when thirteen species
of whiptail lizards composed entirely of females
stay undiscovered due to bias

against such things existing,
we have to meet the universe halfway.
Nothing will unfold for us unless we move toward what
looks to us like nothing: faith is a cascade.
The sky's high solid is anything
but, the sun going under hasn't
budged, and if death divests the self
it's the sole event in nature
that's exactly what it seems.

Because believing a thing's true
can bring about that truth,
and you might be the shy one, lizard or electron,
known only through advances
presuming your existence, let my glance be passional
toward the universe and you.

NOTE

Alice Fulton, "Cascade Experiment," from *Powers of Congress* (Sarabande Books).

APPENDIX B

THE UNCERTAINTY PRINCIPLE IS NOT THE BASIS OF COMPLEMENTARITY

Einstein was tenacious in his efforts to find a way to defeat the uncertainty principle, and his arguments inevitably focus on the question of *disturbance*. But one should not depend on Einstein's framing of the question to frame Bohr's response, since Bohr is continually calling into question the premises of Einstein's challenges. Physicists are well acquainted with arguments concerning disturbances in the form of momentum exchanges; their backgrounds in classical physics make this mode of thinking quite natural. On the other hand, it is certainly *not* part of our training to question the intuitive ontological assumption that individual objects possess inherently determinate properties and that the role of measurement is to reveal such properties. So it is surely the case that Heisenberg's account of uncertainty seems much more intuitive than Bohr's account of indeterminacy, and the fact that Einstein frames the issues in terms of questions of disturbance seems to stack the deck in favor of misunderstanding Bohr's account. But, admittedly, Bohr does not help matters, either: he is sometimes inconsistent in his use of terminology, and his terminological choices sometimes have connotations that conflict with what he otherwise says he is claiming. Despite these occasional rhetorical lapses (which occur even after his philosophy-physics has reached a more mature stage), he is explicit in his disavowal of disturbance as an issue, not only in his 1936 paper, as has been pointed out by many scholars, but also as early as 1927, as I have argued.[1] So one has to proceed with caution in trying to discern the meaning of particular passages: one has to take into account the larger "context," as it were.

There are two articles where Bohr gives considerable attention to his discussions with Einstein concerning the recoiling-slit experiment. One is Bohr's 1949 paper entitled "Discussion with Einstein on Epistemological Problems in Atomic Physics," which was written in honor of Einstein and is primarily an account of their famous debates; the other is Bohr's 1935 response to Einstein, Podolsky, and Rosen. In the 1949 account, Bohr explains that since

> the momentum transfer to the first diaphragm [i.e., the recoiling slit] ought to be different if the electron was assumed to pass through the upper or the lower slit in the second diaphragm [i.e., the two-slit diffraction grating],

Einstein suggested that a control of the momentum transfer would permit a closer analysis of the phenomenon and, in particular, make it possible to decide through which of the two slits the electron had passed before arriving at the plate.

A closer examination showed, however, that the suggested control of the momentum transfer would involve a latitude in the knowledge of the position of the diaphragm which would exclude the appearance of the interference phenomena in question. (Bohr 1963b [1949], 46)

It is important to take note of Bohr's use of the term "latitude." While Bohr unhelpfully places the burden of this "latitude" on our knowledge, rather than, as previously, on the material possibilities for definition, I would suggest that the material possibilities for definition are precisely what is at issue for him in this entire passage. That is, Bohr differentiates between "momentum transfer" and the indeterminacy or "latitude" in the definability of particular variables (the latter of which, he emphasizes, depends on the choice of experimental arrangement). The passage that follows the statement just quoted gives the details of how Bohr uses the *indeterminacy* relations to show that Einstein's recoiling-slit design, while appropriate for determining which-path information, is sufficient to destroy the interference pattern. Indeed, one can review Bohr's (1935, 1949) counterargument to the challenge that Einstein issues in proposing the recoiling-slit experiment and see that, in fact, it does *not* point to any question of disturbance caused by the measurement of which-path information (i.e., by the recoiling slit). Rather, Bohr articulates the essential issue in terms of weighing the semantic-ontic indeterminacies in position and momentum relative to the needed accuracy of the determination of the momentum transfer causing the recoil versus the needed accuracy of the determination of the fringe visibility. Since the indeterminacy in *momentum* must be smaller than the momentum transfer in order for us to have such a determination of momentum (so that we have gathered which-path information), the slit must have a certain degree of mobility, but this will necessarily mean that the indeterminacy in *position* will be quite large (since we need a fixed diaphragm to give meaning to position). How large will this indeterminacy in position be? Bohr calculates *on the basis of the indeterminacy principle* that the indeterminacy in position will in fact be larger than the accuracy needed to distinguish adjacent fringes. Therefore the cost of the determination of which-path information is the destruction of the interference fringes, as a result of the reciprocal indeterminacy of position and momentum:

In particular, it may be shown that, if the momentum of the diaphragm is measured with an accuracy sufficient for allowing definite conclusions regarding the passage of the particle through some selected slit [i.e., the condition for the possibility of defining which-path information] . . . then even the minimum uncertainty [indeterminacy] of the position of the . . . diaphragm compatible with such knowledge will imply the total wiping out of any interference effect. . . . My main purpose in repeating these simple, and in substance well-known considerations, is to emphasize that in the phenomena concerned we are not dealing with an incomplete description . . . but with a rational discrimination between essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location [i.e., fixed diaphragm] or for a legitimate application of the conservation theorem of momentum [i.e., movable diaphragm]. . . . Indeed *we have in each experimental arrangement suited for the study of proper quantum phenomena not merely to do with an ignorance of the value of certain physical quantities* [i.e., uncertainty], *but with the impossibility of defining these quantities in an unambiguous way* [i.e., indeterminacy]. (Bohr 1998 [1935 essay], 77–78; italics mine)

Bohr emphasizes that the issue is one of definability (i.e., indeterminacy), *not* uncertainty, and yet at the same time he relies on the reciprocity relations. There is no inconsistency in this for Bohr because the reciprocity relations are the quantitative expression of the limits of definability—that is, they are an expression of the indeterminacy relations, not the uncertainty principle.

NOTE

1 In addition to Bohr's disavowal of disturbance in his 1927 paper (as discussed earlier), other explicit statements include the following: "Speaking, as is often done, of disturbing a phenomenon by observation, or even of creating physical attributes to objects by measuring processes, is, in fact, liable to be confusing, since all such sentences imply a departure from basic conventions of language which, even though it sometimes may be practical for the sake of brevity, can never be unambiguous" (Bohr 1998 [1938 essay], 104); and "All confusion arises, in fact, from the use of such utterances as 'disturbance of phenomena by their observation,' a phrase equally irreconcilable with any unambiguous meaning of the very words 'observation' and 'phenomena' " (Bohr 1998 [1946 essay], 130).

APPENDIX C

CONTROVERSY CONCERNING THE RELATIONSHIP BETWEEN BOHR'S PRINCIPLE OF COMPLEMENTARITY AND HEISENBERG'S UNCERTAINTY PRINCIPLE

The nature of the relationship between Heisenberg's uncertainty principle and Bohr's complementarity, sparked by the work of Scully et al. (1991), has been a matter of some controversy. The claim of Scully et al. that their experiment offers definitive evidence of the loss of interference without any disturbance caused by the detector has been contested by Storey et al. (1994). Storey et al. argue that complementarity is always enforced by the uncertainty relations, that is, by an uncontrollable momentum transfer (disturbance), thereby arguing that it is the more fundamental principle than complementarity, in contradiction to Scully et al. and the point of view that I espouse here. Wiseman and Harrison (1995) argue that the kind of random momentum kick that Storey et al. enlist to explain the destruction of the interference pattern is in general not the same as the classical notion but rather a strange nonlocal beast involving the "more subtle idea of momentum-kick amplitudes" (*within* an entangled state!) (for more details, see Wiseman et al. 1997). Furthermore, Wiseman and Harrison argue that while the Einstein recoiling-slit gedanken experiment *may* be—but *need* not be—understood in terms of uncontrolled classical momentum kicks, this is not the case for the experiment suggested by Scully et al. (and confirmed by Eichmann et al. [1993]). However, as Wiseman and Harrison point out, such a classical analysis of the recoiling-slit experiment is based on a naive-realist interpretation of the uncertainty principle, which, needless to say, Bohr definitively disclaims. (There may be a lot of controversy concerning Bohr's philosophy-physics, but no scholar will argue that Bohr is a naive realist.)

See also the results of Dürr et al. (1998b), who specifically examine the mechanical effects of which-path detection experimentally and show that "the back action onto the atomic momentum [i.e., momentum kick or disturbance] implied by Heisenberg's position-momentum uncertainty relation cannot explain the loss of interference" (33). Rather, they argue that the "correlations between the which-way detector and the atomic motion [i.e., the entanglement of "object" and "apparatus"] destroy the interference fringes" (33). They also make the point that "correlations between the interfering particle and the detector system are produced in *any* which-way

scheme, for example, in the previously mentioned gedanken experiments of Einstein's recoiling slit and Feynman's light microscope. But in these experiments 'classical' mechanical effects of the detector on the particle's motion can explain the loss of interference as well, so that the effect of the correlations is hidden" (36; italics mine).

Scully et al. attribute *different* mechanisms to the loss of interference in different situations, for example: (1) disturbance via Heisenberg's uncertainty principle in the case of the recoiling-slit experiment (among others), and (2) entanglement in the case of their micromaser cavity detector experiment. They do not offer a general method for sorting out which mechanism is at issue for any given experiment or, more fundamentally, *why* different mechanisms apply. In the absence of such a general explanation, their account is at best incomplete and seemingly ad hoc. If my argument is correct, then disturbance is *never* the mechanism for enforcing the principle of complementarity (not even in the case of the recoiling slit); rather, what is at issue (not just in the clever example of Scully et al., but always) is the intra-action or entanglement of "objects" and "agencies of observation."[1] Indeed, I have argued that, from the beginning, Bohr never accepted a disturbance model of the uncertainty principle but rather understood complementarity as a general relation of reciprocal indeterminacy, which results from the necessary material conditions for the definability of classical concepts as embodied in the material apparatus and manifest in the entanglement of the object and the agencies of observation constituting the objective referent for empirical values obtained during measurement.

NOTE

1 As Wootters and Zurek (1979) and Tan and Walls (1993) show, the disappearance of the interference pattern in the acquisition of which-path information can indeed be accounted for in terms of the entanglement of the states of the photon and the movable diaphragm. (See the derivation of Tan and Walls.) Furthermore, the realization of quantum erasure for a recoiling-slit or a Feynman microscope type of two-slit experiment would support this claim.

NOTES

THE SCIENCE AND ETHICS OF MATTERING

1 Outside of physics circles, one finds that it is often the case that Heisenberg's name is known but not Bohr's. Niels Bohr (1885–1962), a Danish physicist and contemporary of Einstein's, was one of the founders of quantum physics. He won the Nobel Prize in 1922 for his quantum model of the atom. Bohr played a primary role in founding the so-called Copenhagen interpretation of quantum physics. In 1921 he founded the institute in Copenhagen that bears his name. Many of the fundamental contributions to the new quantum theory were born at the institute. Werner Heisenberg (1901–76) won the 1932 Nobel Prize in Physics for "the creation of quantum mechanics," work he did at the Niels Bohr Institute.

2 This is not to suggest that all popular accounts of quantum physics sacrifice rigor to other values and interests, but there is no shortage of such texts that do.

3 This question, from an actual affidavit by Heisenberg, is also uttered by his character in the play. W. Heisenberg, affidavit on the Copenhagen visit, manuscript and typescript, c. 1948, Heisenberg Archive, Max Planck Institute for Physics, Munich (cited by David Cassidy in *Physics Today*, July 2002).

4 This quote from Michael Frayn is from his talk for the Niels Bohr Historical Archive's History of Science Seminar, November 19, 1999 (available on the archive's website).

5 Position and momentum are the quantities that Newton tells us are needed to predict the entire trajectory of a particle—into the future and the past.

6 Frayn, quoted in Justin Davidson, "Was Something Rotten in Denmark?" review of *Copenhagen*, *Newsday*, April 7, 2000, 16.

7 Jungk admits to having been taken in by the "impressive personalities" involved: "That I have contributed to the spreading of the myth of passive resistance by the most important German physicists is due above all to my esteem for those impressive personalities which I since realized to be out of place" (quoted in "David Cassidy letter on Heisenberg," published in F.A.S. Public Interest Report, *Journal of the Federation of American Scientists* 47, no. 6 [November–December 1994]).

8 The documents have been published on the Niels Bohr Archive website. There are some twelve extant drafts of Bohr's letter, written between 1957 and his death in 1962. This is typical of how Bohr wrote and approached physics problems as well. He would go over and over the same ground looking at things from different angles. The drafts are different attempts to get at the heart of what he wanted to say. They don't contradict one another; they offer complementary approaches to the truth. According to Leon Rosenfeld, a coworker, he and Bohr worked on one paper for over ten years and had over one hundred drafts of it.

9 James Glanz, "Frayn Takes Stock of Bohr Revelations," *New York Times*, February

9, 2002. Frayn seems to consider this a small inaccuracy of little significance, but arguably, this error alone might justify a serious rethinking of Frayn's portrayal of Bohr, requiring substantial revision of the play.

10 Frayn fails to mention the fact that even before the momentous engineering project at Los Alamos reached its goal, Bohr visited Churchill and Roosevelt to try to get them to think ahead about the changes brought about by a new atomic age, including steps that might be taken to avoid an arms race. Furthermore, after the war Bohr lobbied for the peaceful uses of atomic and nuclear energy. He was awarded the first Atoms for Peace award for his efforts.

11 I thank Frèdèrique Apffel-Marglin for this point.

12 After floating this conclusion, Frayn subtly distances himself from it. But reporting on an interview with Michael Frayn in the wake of the early release of Bohr's unsent letter to Heisenberg, James Glanz, in an article published by the *New York Times* ("Frayn Takes Stock of Bohr Revelations," February 9, 2002), reveals that Frayn may indeed subscribe to his "strange new quantum ethics": "What does seem to be true in the real world of the audience is that many theatergoers, especially those who have not studied the war and are too young to have lived through it, emerge from performances of the play with an impression that Heisenberg has bested Bohr in their otherworldly debate. With the proviso that he cannot be responsible for how others interpret his play, Mr. Frayn said, *that impression may simply stem from historical fact*. 'Heisenberg didn't, in fact, kill anyone with atomic weapons, or indeed any other weapons,' Mr. Frayn said. 'And Bohr, rightly or wrongly, did actually contribute to the death of many people through the Allied atomic bomb program' " (emphasis added). Clearly, it would have been unwise for Frayn to directly endorse this conclusion in the play. After all, wouldn't it have been a bit too predictable for him to follow Jungk's ironic twist—which lays the moral burden at the feet of scientists who worked on the bomb project for the Allies while turning their German colleagues into heroes—too closely? And given the fact that Jungk recanted his own thesis—that "German nuclear physicists, living under a saber-rattling dictatorship, obeyed the voice of conscience and attempted to prevent the construction of atom bombs, while their professional colleagues in the democracies, who had no coercion to fear, with very few exceptions, concentrated their energies on the production of the new weapon"—wouldn't it have seemed a bit too extreme, to say nothing of historically inaccurate, to simply resurrect this thesis?

13 With ever more irony, perhaps in his enthusiasm to safeguard Heisenberg's reputation using his uncertainty principle, Frayn fails to acknowledge the important fact that Bohr (not Heisenberg) spent decades struggling to come to terms with the larger implications of quantum theory. Moreover, Bohr even raises the very question that interests Frayn: what are the implications of quantum physics for understanding human thought processes? In particular, Bohr uses his notion of complementarity to contemplate the limitations of trying to be aware of one's process of thinking.

14 See especially Frayn 2000, 69. A video clip of this scene is available on the PBS website (listed under "key scene"): http://www.pbs.org/hollywoodpresents/copenhagen/scene/index.html. See also my discussions on the differences between the interpretations of Bohr and Heisenberg in chapters 3 and 7.

15 As I will argue in chapter 3.

16 Frayn 2000, 72.

17 In fact, this is precisely the example that Bohr often used to exemplify complementarity (in a nonphysics context). It is a lesson discussed in a little book by Paul Martin Møller called *The Adventures of a Danish Student*. Bohr was so impressed with its exemplary example of complementarity that he would present a copy to all guests of the Niels Bohr Institute.

18 See chapter 2 for a detailed discussion of my methodological approach.

19 Inevitably some readers will balk at my use of "best" as a descriptor for either kind (indeed any kind) of theory. But it is a mistake to think that normative concerns entail a normative foundationalism or progressive conceptions of knowledge and history. For a more detailed discussion, see Rouse's (2002, 2004) account of normativity and naturalism. Furthermore, my account of scientific practices is not naturalistic in the sense of giving science unquestioned authority to speak for the world, on the contrary; Rouse argues that a suitably revised conception of naturalism takes seriously what our best scientific theories tell us while simultaneously holding science accountable for its practices, for its own sake as it were, in order to safeguard its stated naturalist commitments. Indeed, the unquestioned authority of science does not get a free pass here; on the contrary, the point is that a strong commitment to naturalism in Rouse's sense makes it possible to call its presumed authority into question on its own terms.

20 When diffraction and interference were first discovered, they were thought to be physically distinct and were identified by different terms: "diffraction" referred to the bending of waves, and "interference" referred to their overlap. Some physicists maintain this historical distinction; others don't. In his famous lectures (1964), the Nobel laureate physicist Richard Feynman suggested dropping the distinction, since there is only one basic phenomenon at issue: physically speaking, diffraction and interference are one and the same; they both have to do with the fact that when waves overlap, their amplitudes combine.

21 Technoscience and naturecultures are now commonly used terms in the science studies literature. As Donna Haraway (1997) explains: "Technoscience extravagantly exceeds the distinction between science and technology as well as between nature and society, subjects and objects, and the natural and the artifactual that structured the imaginary time called modernity. . . . Like all the other chimerical, condensed word forms that are cobbled together without-benefit-of-hyphen in the hyperspace of the New World Order, Inc. the word technoscience communicates the promiscuously fused and transgenic quality of its domains by a kind of visual onomatopoeia" (3–4).

22 I do not assume that practices require intentional actions, or rather, I do not assume that intentionality is an exclusively human activity, aligned with will or subjectivity, for example, or even that humans are the locus of intentional interactions. On the contrary, I reconceptualize intentionality as a material intra-action (see chapters 4 and 8).

23 The notion of "intra-action" is a general term that speaks to the nature of being. In particular, it is not a concept that is limited to the microscopic domain. That is, although quantum physics provides unambiguous empirical evidence for the existence of intra-acting (rather than interacting) agencies, this *ontological* notion is completely general, and, in particular, is not limited in its applicability to microscopic objects. (Of course, it's an empirical question whether or not there are different ontologies at different length scales, but at least so far there is no evidence that that is the case, and contemporary physics does not incorporate such a belief. See chapter 7 for a discussion of the question of decoherence.)

24 With terms like "interventions" and "consequences" suitably redefined.

ONE • MEETING THE UNIVERSE HALFWAY

1 In the original text from which this passage is drawn (Barad 1996b), I deployed the term "social constructivism" for rhetorical purposes as part of an overall strategy aimed at destabilizing the realism-versus-constructivism debate (as the tensions in this paragraph self-consciously enact). To be clear, I am *not* a social constructivist, a point that should be understood from the very naming of the alternative I propose: "agential realism." My hoped-for intervention at this historical juncture was to point out that, despite the heated debates of the mid-1990s, there was sufficient play in both of these terms to render the debate meaningless. Indeed, I choose the subtitle "Realism and Social Constructivism without Contradiction" as a direct index of the futility of a debate centered on terms that are indeterminate. An alternative subtitle such as "Beyond Realism and Social Constructivism" might have been more direct in some ways, but "beyond" speaks of transcendence in a way that is misleading and the moment seemed to cry out for a more poignant marker of the senselessness of this tired debate. Actually, I originally had a very different subtitle: "Ambiguities, Discontinuities, Quantum Subjects, and Multiple Positioning in Feminism and Physics," which I changed at the last moment because the debate was growing in ferocity with the consequence that there was less productive interchange across the "divide." The agential realist view that is put forward in the paper, and in this book, cuts across the traditional divide between realism and social constructivism; that is, it challenges the very terms of the debate. (In particular, the "halfway" in the title is *not* a way of marking agential realism as an attempt to find some "middle ground" between social constructivism and scientific realism, as has been suggested. This suggestion is entirely misguided.) The point is that agential realism calls into question representationalism, individualism, and other foundationalist assumptions that prop up *both* traditional forms of realism and social constructivism.

2 A less obvious point perhaps is that the success of scientific theories is not automatic for realists either, as Laudan (1981) and Fine (1984) argue.

3 For Galison, stability refers to the invariance of results under changing experimental conditions (rather than the narrower category of manipulation), and directness is an epistemological, but not necessarily logically noninferential, matter.

4 Ontology has been given increasingly more attention in science studies since I originally offered these observations (Barad 1996). See, for example, Cussins (1998); Haraway (2003); Latour (1999); Law and Singleton (2000); Mol (2003); and Stengers (1997). While this is not intended to be an exhaustive list, and it is encouraging that the literature on ontology has grown significantly, my original point—that the bulk of attention in science studies has been and continues to be devoted to concerns about the nature of knowing rather than the nature of being—still holds.

5 For further discussion of "ontoepistemology" (the study of the intertwined practices of knowing and being), see chapter 4.

6 Cushing asserts that "realism is in double jeopardy." The sense in which he intends this remark is best illustrated in terms of his example, which centers on the competing interpretations of quantum physics offered by Niels Bohr (the so-called Copenhagen interpretation) and David Bohm. First, Cushing argues that realism is called into question by the almost universally accepted "antirealist" Copenhagen interpretation. And furthermore, realism is challenged by the very existence of competing theories that are empirically indistinguishable. Although I will be arguing here for a realist stance on Bohr's part (as opposed to Cushing's antirealist reading of Bohr), this divergence in and of itself does not weaken the underdetermination aspect of Cushing's argument. (Note that there are a few important unresolved issues not made explicit in Cushing's argument. One is that the empirical equivalence of these theories depends on the resolution of the measurement problem for the Copenhagen interpretation [see chapter 7]. And it still remains to be seen whether Bohm's theory and the Copenhagen theory are empirically coincident in all respects.) In any case, while underdetermination may pose a problem for the correspondence theory of truth, it does not preclude realist positions according to my rendering of "realism" (see hereafter).

7 See Barad 1995 for a further discussion of "play" in the culture of science.

8 This fact isn't at all surprising to those who realize that a substantial number of feminist science studies scholars, including many of the most highly regarded scholars in the field, are scientists or at least have significant training in the sciences.

9 Rather blasphemously, agential realism denies the suggestion that our access to the world is mediated, whether by consciousness, experience, language, or any other alleged medium. See the discussion hereafter and in chapter 4. Rather like the special theory of relativity, agential realism calls into question the presumption that a medium—an "ether"—is necessary.

10 The neologism "ontoepistemological" marks the inseparability of ontology and epistemology. I also use "ethico-onto-epistemology" to mark the inseparability of ontology, epistemology, and ethics. The analytic philosophical tradition takes these fields to be entirely separate, but this presupposition depends on specific ways of figuring the nature of being, knowing, and valuing. See chapters 4 and 8 for further discussion.

11 See especially the chapter "The Data of Biology" in *The Second Sex*. Unlike some

recent feminist attempts to rethink the body, Beauvoir displays an unapologetic willingness to engage important biological dimensions of embodiment. Of course, her willingness may seem like so much naiveté at this historical juncture, but it is refreshing to read excerpts from this chapter which may be usefully meditated on by contemporary feminists in order to help recalibrate the possibilities for direct engagement with the body's biology.

12 It is important not to conflate poststructuralism with postmodernism. Both terms refer to complex sets of discourses, but a brief explanation of the differences between them might usefully be understood in the following way. Postmodernisms are concerned with a critique of modernism. Poststructuralism concerns itself with a radical critique of individualist ontologies, especially as found in the notion of the liberal humanist subject. Poststructuralism focuses on the productive nature of social practices and the discursive constitution of the subject. Michel Foucault's and Judith Butler's poststructuralist accounts are taken up later in this book.

13 See Grosz's *Volatile Bodies* (1994) for a detailed discussion of the limitations of both "internal" and "external" accounts.

14 Readers unfamiliar with these issues may want to consult any one of a number of introductory texts on feminist theory and poststructuralist theory.

15 Note that representationalism is not a prohibition against talk about "representations," nor does it take the notion of representations to be meaningless. The issue at hand is what role representations play and how referentiality is conceived.

16 Rouse begins his interrogation of representationalism in *Knowledge and Power* (1987), wherein he examines how a representationalist understanding of knowledge gets in the way of understanding the nature of the relationship between power and knowledge. He continues his critique of representationalism and the development of an alternative understanding of the nature of scientific practices in *Engaging Science* (1996). Rouse proposes that we understand science practice as ongoing patterns of situated activity, an idea that he further elaborates in *How Scientific Practices Matter* (2002).

17 The allure of representationalism may make it difficult to imagine alternatives. I discuss performative alternatives hereafter, but these are not the only ones. For example, Foucault points out that in sixteenth-century Europe, language was not thought of as a medium; rather, it was simply "one of the figurations of the world" (1970, 56), an idea that reverberates in a mutated form in the posthumanist performative account that I offer.

18 While Andrew Pickering has been one of the few science studies scholars to take ownership of this term, there is surely a sense in which science studies theorists such as Donna Haraway, Bruno Latour, and Joseph Rouse also propound performative understandings of the nature of scientific practices. In *The Mangle of Practice*, Pickering explicitly eschews the representationalist idiom in favor of a performative idiom. It is important to note, however, that Pickering's notion of performativity would not be recognizable as such to poststructuralists, despite their shared embrace of *performativity* as a remedy to representationalism, and despite their shared rejection of humanism. Significantly, Pickering, in his appropriation of the term, does not acknowledge its politically important—arguably inherently queer—genealogy (see Sedgwick 1993), or why it has been and continues to be important to contemporary critical theorists, especially feminist and queer studies scholars and activists. Indeed, he evacuates its important political history along with many of its crucial insights. This is perhaps not surprising given that Pickering ignores important discursive dimensions of scientific practices, including questions of meaning, intelligibility, significance, identity formation, and power, which are central to poststructuralist invocations of performativity and feminist accounts of technoscientific practices. And he takes for granted the humanist notion of agency as a *property* of individual entities (such as humans, but also weather systems, scallops, and stereos), which poststructuralists problematize. On the other hand, poststructuralist approaches fail to take account of "nonhuman agency," which is a central focus of Pickering's and other performative accounts of scientific practices.

19 As the historian of science David Cassidy (1999) describes it, at this historical juncture there was a move away from the mechanistic worldview in favor of the energetic and electromagnetic views and Einstein was a member of a dwindling minority in holding on to the hope for a unified mechanistic account of nature. In fact, although the notion that the atom is indivisible (as its namesake suggests) was already coming apart around the edges with J.J. Thomson's 1897 discovery of the electron, it wasn't until Einstein's 1905 explanation of Brownian motion that physicists were convinced that atoms are material particles and not merely theoretical entities. The die-hard positivist Ernst Mach was a notable holdout.

20 See chapter 8.

21 Nancy Cartwright also makes this distinction. Like Hacking, she is a realist toward entities and not theories. While Hacking focuses on experimental practice, Cartwright pays more attention to the intricacies of theorizing and model building.

22 See, for example, the chapter "Microscopes" in Hacking 1983.

23 Of course, "zooming in" on any practice of image formation—including the use of point-and-shoot cameras—will make it clear that images don't simply capture what is already there.

24 Valerie Hanson (2004) suggests using the notion of "haptic vision" practices to understand STM image formation.

25 The distinction between physical touch and the interaction between the microscope tip and the sample is not as great as one might think. "Touching" as we know it in our everyday lives is an electromagnetic interaction, a repulsion between electron clouds that don't so much "touch" in the sense of encountering each other's boundaries through physical contact as sense one another's electron clouds; and furthermore, the gap between the STM tip and the surface atoms involves a separation of a mere few nanometers, so the question of whether this is "really touching" in the sense of physical prximity is moot.

26 That is, according to the principles of classical Newtonian physics, the particles

shouldn't be able to cross the barriers, but they do because of the quantum mechanical wave nature of matter. The "dual" (wave-particle) nature of matter is discussed in detail in chapter 3.

27 Gerd Binning and Heinrich Rohrer of the IBM Zurich Research Labs created the STM in March 1981. They received the 1986 Nobel Prize in Physics for their contribution.

28 Bohr eschews representationalism and moves toward a performative account, where scientific practices entail direct material engagement with the world rather than reflection from afar. Unlike Hacking, though, Bohr does not take account of the dynamics of practice (e.g., the fact that part of the difficulty of an experiment is getting the equipment to work; an experimental setup doesn't simply appear ready for the task at hand). See chapter 4.

29 Paul Teller (1989) calls this "particularism" (see chapter 7).

30 For some readers, the term "phenomenon" will no doubt carry what for my purposes are unwanted phenomenological connotations. Crucially, the agential realist notion of *phenomenon* is not that of philosophical phenomenologists. In particular, phenomena should *not* be understood as the way things-in-themselves *appear*: that is, what is at issue is not Kant's notion of phenomena as distinguished from noumena. Rather, as will be explained in later chapters, my notion of phenomenon is an elaboration of Bohr's notion of phenomenon. I preserve the term not merely to honor Bohr but to underline the important shift that an agential realist understanding of phenomena plays in reconsidering the foundational or interpretative issues in quantum mechanics (see chapter 7). And last but not least, I preserve the term "phenomenon" because of its common usage, especially in the scientific realm, to refer to that which is observed, what we take to be real. This is useful because when the term is invoked an opportunity presents itself for the possibility of getting the objective referent right—that is, of associating the term with the full complexity that is a "phenomenon" in the agential realist sense (see especially chapter 4).

31 Rouse makes this point about experimenting and theorizing as well; see especially Rouse 2002.

32 "Intra-action" is a core concept in my agential realist account. I discuss it in detail in later chapters (see especially chapters 3 and 4).

33 Unless, of course, you take "things" to be collectives. This is the strategy that Latour advocates in his recent work: redefining the term "thing" (through a reclamation of its etymological roots) to stand for the human-nonhuman collective that is assembled. See especially Latour 2004 and the introduction to the catalog for the exhibit Making Things Public—Atmospheres of Democracy, http://www.ensmp.fr/latour/articles/article/96-DINGPOLITIK2.html. However, not nearly as much effort has been put into dislodging "words" (in the "words and things" staging of representationalism)—that is, questions related to discursive practices (the material conditions for meaningful expression)—especially in relation to issues that Foucault would consider to be at the crux of the discourse-power-knowledge nexus, that is, the discursive constitution of the subject. This is precisely the point that needs attention.

34 Crucially, this statement must be understood with an appreciation of the Foucauldian point that disciplinary power is not an external force that acts on the subject; rather, there is "only a reiterated acting that is power in its persistence and instability" (Butler 1993, 9).

35 Few feminist science studies scholars take poststructuralist insights seriously (that is, take them into account in any systematic fashion). Haraway and Rouse are notable exceptions.

36 See chapter 4. Also see the discussion in chapter 7 on the use of auxiliary apparatuses that take the measuring agencies (of the original system—for example, laboratory practices) to be (in this new configuration) part of the system under investigation. Significantly, as I explain, the addition of an auxiliary apparatus entails the constitution of a new phenomenon.

37 The metaphors of governmental politics in this paragraph are Latour's (2004), but the difficulties I am highlighting are not his alone.

38 See introduction, note 19.

39 Most of these multiple and various engagements trace performativity's lineage to the British philosopher J. L. Austin's interest in speech acts, particularly the relationship between saying and doing and the productive rather than merely descriptive efficacy of certain speech acts. Derrida is usually cited next as offering important poststructuralist amendments. For Derrida, the effectiveness of a speech act is not due to the originating will of a subject, or the situational context in which the citation occurs, as Austin suggests; rather, it is through iterative citationality that discourse gains the power to bring about what it names. Butler elaborates Derrida's notion of performativity through Foucault's understanding of the productive effects of regulatory power in theorizing the nature of identity as performative. Butler introduces her notion of gender performativity in *Gender Trouble*. In *Bodies That Matter*, Butler argues for a linkage between gender performativity and the materialization of sexed bodies. My sketch of the complex genealogy is far too coarsegrained and simplified to do the topic justice here. See Eve Kosofsky Sedgwick (1993) for more details.

40 See especially Foucault 1978. Butler cites a range of sources from the feminist science studies literature on the gendered construction of "sex."

41 Quoted in Butler 1990, 106 (italics mine).

42 Foucault writes: "Power is not something that is acquired, seized, or shared, something that one holds on to or allows to slip away. . . . Power is not an institution, and not a structure; neither is it a certain strength we are endowed with. . . . Power's condition of possibility, or in any case the viewpoint which permits one to understand its exercise, even in its more 'peripheral' effects, and which makes it possible to use its mechanisms as a grid of intelligibility of the social order, must not be sought in the primary existence of a central point, in a unique source of sovereignty from which secondary and descendent forms would emanate; it is the moving substrate of force relations which, by virtue of their inequality, constantly engender states of power, but the latter are always local and unstable. [P]ower . . . is produced from one moment to the next, at every point, or rather in every relation from one point to another" (Foucault 1978, 92–94; reordered).

43 See also Kirby 1997 and Cheah 1996 on this point.

44 See also Butler 1989.

45 The agential realist terms "material-discursive" and "intra-action" are defined later. It is perhaps important to note in relation to the foregoing discussion that the hyphen in "material-discursive" is not simply a convenient way to make a conjunction out of otherwise disparate terms but rather denotes a theorized joining of the two. See chapter 4.

46 Strictly speaking, agency is not a property of entities—whether "human," "nonhuman," or "cyborgian." On the contrary, the differential constitution of the "human" and the "nonhuman" is agentially enacted, as I discuss in chapter 4.

47 Donna Haraway's work is explicitly and tenaciously posthumanist in this sense (even if she doesn't use the label). Indeed, Haraway's scholarly opus—from primates to cyborgs to companion species—develops a complex understanding of the technoscientific practices through which the various differentiations of the "human" and its others are enacted.

Notably, this notion of posthumanism differs from Andrew Pickering's idiosyncratic assignment of a "*posthumanist* space [as] a space in which the human actors are still there but now inextricably entangled with the nonhuman, no longer at the center of the action calling the shots" (1995, 26). While Pickering thereby decenters the human from his accounts of scientific practice, he nonetheless takes the human, and its distinction from the nonhuman, for granted. (Note that Pickering's notion of "entanglement" is explicitly epistemological, not ontological.) What is at issue for him in dubbing his account "posthumanist" is the fact that it is attentive to the mutual accommodation, or responsiveness, of human and nonhuman agents. While Pickering (1995) identifies his account of the "mangle of practice" as specifically "posthumanist" and "performative," his use of both these key terms is very different from mine. Ironically, the liberal humanist actor that makes choices in the context of scientific practices is everywhere evident in his theory.

I distinguish my specific invocation of "posthumanist" from other uses as well, such as the notion that the posthuman designates an era following the "end of man." My use of posthumanism is also to be contrasted with (anti)humanism and its attendant anthropocentrisms. Furthermore, I am not drawing a contrast between some posthuman entity and its human predecessor. Rather, in an unsettling of (anti)humanist assumptions, I want the focus to be on the boundary-making practices that delineate human from other. For further discussion, see chapter 4.

48 While physicists, philosophers, historians, and others talk of *the* Copenhagen interpretation, in an important sense there are really many Copenhagen interpretations; or to put it another way there is no determinate or well-defined, coherent, and complete Copenhagen interpretation. The physicists who contributed to the Copenhagen interpretation displayed significant philosophical and interpretative differences in their specific contributions, so that what is taken to be *the* Copenhagen interpretation is actually a superposition of the disparate views of a group of physicists who include Bohr (complementarity), Heisenberg (uncertainty), Born (probability), and von Neumann (projection postulate), to name a few of the key players. Beller (1999) also argues that the Copenhagen interpretation is not a coherent framework but rather a compromise that was achieved among the key players.

49 See Cushing 1994 on the hegemony of the Copenhagen interpretation of quantum mechanics.

50 In the mid-1990s, the foundational issues in quantum theory started to become a respectable topic of conversation in physics (once again) in large part due to related developments in quantum information theory, including applications to quantum cryptography, quantum teleportation, and quantum computing (see chapters 7 and 8).

51 Increasingly, quantum textbooks do not mention any of Bohr's contributions to the field (except for reference to his model of the atom, which predates the full theory of quantum physics). In particular, there is often no mention of his principle of correspondence and the role it played in the development of the quantum theory, or complementarity and its importance to an understanding of quantum theory. The implicit justification is that these are "mere historical facts" of no practical or computational consequence, which means "of no real significance." But this turns out not to be the case (see chapter 7).

52 See chapter 7.

53 See "Methodological Interlude" in chapter 3. It would not be unreasonable to think that Bohr would find himself in sympathy with this approach, which attempts to be attentive and accountable to our specific engagements with, and as part of, the world as opposed to merely honoring his authority. In his stance toward the world, it is evident that intellectual integrity trumps authority.

54 For Bohr, "complementary" means simultaneously necessary and mutually exclusive (as explained in detail in the next section). See Bohr 1963b, vol. 2, for examples of this approach. One often-noted example of the failure of Bohr's analogical methodology is his attempt to resolve the vitalism-mechanism debate in biology. His approach seems to have failed because he assumed, from his limited technological perspective, that the conditions for examining the underlying mechanics of life processes and the conditions for maintaining the life of the specimen under investigation were mutually exclusive. On the other hand, the question how "life" ought to be defined is perhaps more complex than some of Bohr's critics acknowledge (see Barad, "Living in a Posthumanist Material World: Lessons from Schrödinger's Cat").

55 It is important to note that the fact that Newtonian physics "works" (i.e., it gives adequately accurate numerical values in its predictions) in the macroscopic domain does not mean that Newtonian physics is a strictly true theory in the macroscopic domain (or any other); in fact most physicists do *not* believe that to be the case or that the assumptions of measurement transparency (i.e., the metaphysical background assumptions that support Newtonian physics) hold in that domain (see chapter 3). Rather, the fact that Newtonian physics makes predictions that are approximately the same as those made by quantum theory in the macroscopic domain is simply due to the fact that in this domain the ratio of Planck's constant to the mass of the particle is generally smaller than the

accuracy required of the macroscopic situation in question—but it is *not* zero. And the fact that this ratio is not strictly zero is the key point. In other words, the fact that Newtonian physics provides good approximations to the exact quantum mechanical solutions for many macroscopic situations is not evidence against the new epistemology or ontology suggested by my elaboration of Bohr's account, which is in fact supported by the new experiments that have far-reaching implications for the foundations of quantum theory. Indeed, there is no evidence to suggest that there are two separate "worlds"—the Newtonian (macro) world in which Newton's equations apply, and the quantum (micro) world in which Schrödinger's equation applies. In fact, as Bohr points out, the reverse seems to be the case: once the epistemological (and ontological) shift suggested by quantum theory is made, we can understand why the old assumptions weren't readily questioned and lay hidden for centuries. This is why Bohr refers to the *general* epistemological lessons of quantum theory. For further discussion, see chapter 3.

TWO • DIFFRACTIONS

1 For a discussion of reflexivity in the science studies literature, see, for example, Woolgar 1988a.

2 In her essay "The Promises of Monsters," Haraway (1992) proposes the notion of diffraction as a metaphor for rethinking the geometry and optics of relationality. In her book *Modest—Witness*, Haraway (1997) promotes the notion of diffraction to a fourth semiotic category. My elaboration does not follow a semiotic course of analysis; rather, in carefully exploring the details of diffraction as a physical phenomenon and a methodology, my elaboration engages with and helps me reformulate the notion of discursive analysis. Attending to quantum aspects of diffraction phenomena I also examine in detail the notion of entanglement and propose a rethinking of space, time, and matter that, among other things, shows the need to take account of topological as well as geometrical reconfigurings in genealogical analysis.

3 It's easy to make a diffraction pattern for yourself. Facing a light source, hold two fingers very close together (but without touching) in front of one of your eyes. Look carefully. You should be able to detect lines of dark and light between your fingers. Try varying the distance between your fingers and observe the change in pattern. Diffraction patterns vary with the size of the slit. The pattern also varies with the wavelength (color) of the light and the distances between slits if there is more than one.

4 The light source used to make this image is monochromatic (one wavelength) and coherent (the waves are in phase—that is, in lock step—with one another).

5 Superposition is discussed in more detail in chapters 3 and 7. As we will see, superpositions in quantum mechanics have far-reaching implications.

6 A wave has two important characteristics: amplitude and wavelength. The wave's amplitude is its height (i.e., the relative size of the disturbance). The wavelength is the distance between the wave's crests. The amplitude of a wave is related to its intensity (or brightness in the case of light waves). The relative *phase* of component waves in a waveform relates similar features to one another (e.g., one may speak of the relative phase of the crests of the component waves). When the component waves in a waveform are lined up with one another, they are said to be "in phase."

7 It is perhaps also worth noting that "interference" can be a misleading term for the novice, since the verb "to interfere" carries the connotations of disruption, hindrance, or obstruction. When waves meet, they don't disrupt or obstruct each other, no impact or collision occurs, as in the case of two particles. On the contrary, the whole point is that the waves can coexist unhindered by each other's presence; they can overlap in a common spatial region—indeed, at a single point. There are wonderful online interactive programs for learning about diffraction and interference. See, for example, the Physics Java Applets page by Chiu-king Ng, a high school physics teacher in Hong Kong, http://www.ngsir.netfirms.com/englishVersion.htm#lightwave. See p. 407, n.20.

8 The actual pattern depends on specific features including the wavelength of the waves, the width of the slits (holes), and the distance between them. In particular, for a given diffraction grating (breakwater), different wavelengths will constructively and destructively interfere at different places on the screen (the shore or another surface). This explains why diffraction gratings separate white light into different component colors (effectively acting like a prism).

9 Physically speaking, diffraction and interference are one and the same. They both have to do with the fact that when waves overlap, their amplitudes combine.

10 A single-slit diffraction pattern also exhibits bands of constructive and destructive interference. You can find an explanation of single-slit diffraction in terms of the interference of "wavelets" (using Huygen's principle) in elementary textbooks on optics.

11 This is called a Poisson spot. This phenomenon played an important historical role in debates about the wave-versus-particle nature of light. In 1818, hoping to disprove the ridiculous conjecture that light is a wave, Siméon Poisson submitted a paper in a scientific competition sponsored by the French Academy of Sciences wherein he deduced the "ludicrous" conclusion that if light were a wave there would be a bright spot in the center of a shadow cast by a round opaque object. Much to his chagrin, in short order one of the judges, Dominique Aargo, performed the experiment and observed the resulting bright spot at the center of the diffraction pattern.

12 When sunlight, which contains the full spectrum of colors in the visible part of the electromagnetic spectrum, passes through a diffraction grating, the overlapping of light waves results in the enhancement of some colors in some regions of the disc and the diminishment (or elimination) of others. Which colors are enhanced and which are diminished in particular regions depend on the wavelength of the light wave, that is, on its color. Thus different regions are differently colored.

13 The various colors that make up white light are separated here as a result of the

light waves from either side of the thin film interfering or overlapping with one another, increasing the intensity of some colors at some positions and decreasing or even eliminating others. Note: The coloration of soap bubbles and other thin films is usually said to derive from interference, as contrasted with diffraction. Again, I am not making a distinction between the terms, since they ultimately depend on the same physics.

14 The first screen to the left with a single slit is there for technical reasons: to ensure that the light going through the diffraction grating is "coherent," that is, the waves going though the diffraction slits have a fixed phase relationship. It is also assumed that a monochromatic (i.e., single wavelength) light source is used. The significance of the fact that the diffraction grating is made of two parts such that one slit is bolted to the platform and the other is supported by two springs will be taken up later (see chapters 3 and 7).

15 Many introductory texts on quantum physics discuss this important experiment. See, for example, Eisberg and Resnick 1974. It is an interesting historical fact that following a (lucky) break in the vacuum and reheating of the crystal sample, the structure of the crystal changed, serendipitously changing the nature of Davisson and Germer's original experiment from a frustrating failure into definitive experimental confirmation of de Broglie's matter wave hypothesis. See *Physics Today* 31, no. 1 (1978): 34–41. G. P. Thomson, who used a different diffraction technique to show evidence for the *wave* nature of electrons in the early days of quantum mechanics, shared the Nobel Prize with Davisson. G. P. Thomson was the son of J. J. Thomson, who won a Nobel Prize in physics for discovering the electron, that is, showing it to be a new elementary *particle*.

16 The wave-particle duality paradox is discussed in detail in chapters 3 and 7.

17 This is important to keep in mind when we get to the methodological questions. If the goal of reflexivity is to analyze the "instrument" (e.g., the investigator's role in helping to constitute the evidence) along with the data, reflection is the wrong metaphor. While diffraction can be used to read both the instrument and the object through each other in a way in which the identifications of "subject" and "object" are not fixed, reflection has an asymmetrical focus that fixes one as the standard (i.e., a fixed mirror) against which the other is read. (Appreciating the difference between geometrical and physical optics—discussed in the next paragraph—will help drive home this point.) Turning the mirror around, as it were, is a bad method for trying to get the mirror in the picture.

18 Newtonian physics (sometimes also called "classical physics") was a very successful paradigm that governed physics for hundreds of years before the advent of quantum physics in the early twentieth century.

19 The notion of a "ray" of light reduces all concerns about light to its path or trajectory. In geometrical optics, this invocation is not intended either epistemologically or ontologically; "ray" merely serves as a useful heuristic.

20 What makes this analogy rigorous mathematically is the notion that a de Broglie wavelength can be associated with each particle of mass. Eisberg and Resnick 1974, a commonly used undergraduate text, discusses this analogy in detail.

21 See chapter 1 for a detailed discussion of representationalism.

22 The "strong programme" in the sociology of scientific knowledge (SSK) adopted it as one of its four basic tenets. For an in-depth discussion and advocacy of reflexivity in science studies, see especially Woolgar 1988a, 1988b. See also the discussion of the "epistemological chicken debates" in Pickering 1992.

23 See, for example, discussions in Harding 1991; Traweek 1992; Haraway 1997; and Rouse 1996.

24 On this point, see especially Haraway 1997, 35. The feminist science studies literature is replete with examples of how gender is made together with science. Keller (1985), in one of the founding works of feminist science studies, made this point clear more than two decades ago: gender and science are co-constituted; the point is not women in/and science, or gender in/and science, but gender-and-science-in-the-making.

25 If diffraction is to serve as an important metaphor for differences that matter, it is crucial that we pay attention to the kinds of differences that different understandings of diffraction evoke, so as to not conflate questions of accountability to differences that matter with postmodern celebrations of difference for difference's sake. In this regard it is worth noting that although Thomas Young, who first proposed the famous two-slit experiment, theorizes diffraction as being about differences, his notion of difference relies on sameness as a primary category as well as the fixity of place: "In order that the effects of two portions of light may be thus combined it is necessary that they be derived from the *same origin*, and that they arrive at the *same point* by different paths, in directions *not much deviating from each other*" (quoted in Kipnis 1991, 88; italics mine). Presumably a "mutated modest witnesses" of the Second—Millennium (Haraway) wouldn't want too quickly to embrace this conception. See Barad 1997.

26 Some may argue that all thinking is metaphorical in some sense, but this does not affect the point I am making.

27 The inanimate-animate distinction is perhaps one of the most persistent dualisms in Western philosophy and its critiques; even some of the most hard-hitting critiques of the nature-culture dichotomy leave the animate-inanimate distinction in place. It takes a radical rethinking of agency to appreciate how lively even "dead matter" can be.

28 Quantum electrodynamics is one of the most successful theories ever developed in physics. It is successful in accounting for measured phenomena that span 25 orders of magnitude, from subnuclear dimensions (10^{-16} cm) to distances as large as 10^9 cm (confirmed using satellite measurements). The degree of agreement between theory and experiment is equivalent to determining the distance from New York City to Los Angeles to within the width of a hair.

29 Some of the scholarship in gender and science studies has been limited in important ways by its primarily unidirectional method of questioning. And bidirectionality doesn't cut it, either—this isn't simply a two-way street (although adding to the usual set of considerations investigations of how women's studies might include more science in its curriculum would be a nice addition). The point is, as I have argued, a diffractive engagement of feminism and science has much more to offer than unidirectional or even multidirectional approaches.

30 "Transdisciplinarity" has a sense of the kind of perspective I'm interested in, but it is not sufficiently robust as generally explicated. This will become increasingly evident with the further elaboration of agential realism. See also Barad 2000 for a discussion of the pedagogical implications.

31 I take it as a given that not all disciplinary, multidisciplinary, or transdisciplinary fields of knowledge are restricted to academic learning.

THREE • NIELS BOHR'S PHILOSOPHY-PHYSICS

1 For a detailed discussion of how waves passing through a two-slit diffraction grating can produce diffraction or interference patterns, see chapter 2. The following discussion builds on the points made in that chapter and explains why and how the two-slit experiment is useful in distinguishing wave and particle behaviors.

2 It is important not to skip over this fact too lightly. One needs to take in the profundity of this achievement. Not only was Maxwell able to show that two seemingly disparate phenomena—electricity (e.g., the flow of electrons that causes light bulbs to glow) and magnetism (e.g., the attraction of iron filings by magnets)—not obviously related were indeed different manifestations of one phenomenon, but he was also able to show in the context of this unified view that light is an electromagnetic wave. Furthermore, this theory provided the basis for Einstein's special theory of relativity (1905). Ironically, in that same year (1905), Einstein wrote a paper suggesting the particle nature of light, for which he won the Nobel Prize in physics (contrary to the popular but mistaken impression that he was awarded the prize for the theory of relativity).

3 See, for example, Kuhn 1978 for details on the empirical evidence leading to the paradox of wave-particle duality.

4 It is important to understand that amid all this confusion was a deep sense of order, for despite the seemingly contrary results—sometimes particles, sometimes waves—experimental outcomes showed both consistency and reproducibility: given a particular experimental configuration that exhibits particle-like behavior, this setup always yields particle-like behavior, never wavelike behavior; likewise, there is consistency and reproducibility in the exhibition of wavelike behavior, given an appropriate alternative experimental apparatus. And so it was on this basis that the "dual" nature of light was taken very seriously. To Bohr the consistency and reproducibility of the experimental results, however surprising the results themselves may be, gave him faith that it would be possible to find a coherent framework. Indeed, these factors were fundamental to his development of the principle of complementarity.

5 For example, in the case of ocean waves, waves are particular distrubances of the water, not some separate entity in the water. Indeed, this was the motivation behind the discussion concerning the reality of an ether in the nineteenth century: What medium gave "support" to electromagnetic waves? What was the substance that was actually doing the "wiggling"? With the acceptance of Einstein's special theory of relativity, the notion of an ether was eliminated from modern physics. What does the "wiggling" in the case of electromagnetic waves is the electromagnetic field.

6 The unfortunate term "wavicle" has sometimes been wielded as a triumphant symbol of the quantum resolution of the wave-particle duality paradox. For example, if the ontological question is raised as to whether light or matter is *really* a wave or a particle, one will sometimes hear the confident reply, meant to settle all questions, that they are wavicles, as if the introduction of this new term settles the ontological contradiction at hand. But without any specification of the defining characteristics of a "wavicle" (outside a circular definition that summarizes the dual nature of light), the term refers to nothing more than a simple refusal to deal with the challenges presented by the duality of light and matter.

7 "The contemplation of such more or less practical arrangements and their more or less fictitious use proved most instructive in directing attention to essential features of the problems" (Bohr 1963b [1949 essay], 50).

8 Similarly, suppose that we perform the same type of experiment using a light source, instead of electrons. If we use a relatively high intensity light source, we observe the usual interference pattern for waves. But suppose we use a very weak intensity light source. In this case we can watch each spot of light appear on the screen one at a time, just as the electrons did. (Note: When light behaves like a particle, it is given the more appropriate particle-like moniker "photon.") In principle, the foregoing findings and analysis apply equally to photons or electrons.

9 Figure 11 is not a diagram that Bohr actually drew, though it is implied in the combination of his figures 4 and 5, reproduced here in figure 8. This particular version is from Bertet et al. 2001. It is a variation on the which-path experiment suggested by Bohr where both slits are suspended on a spring instead of the single slit shown here.

10 This remarkable experiment has the added benefit of parsing out important differences between Bohr's and Heisenberg's views on the nature of uncertainty (or rather, indeterminacy—this point is taken up later in this chapter). In fact, experiments of this kind enable us to provide *empirical* answers to important *metaphysical* questions. See chapter 7 for details.

11 Although one is free to give either a realist or an antirealist interpretation of Newtonian physics, the "classical realist" one is particularly seductive to our Enlightenment intuitions, and I have heard variations of this classical realist tenet espoused time and again to students in undergraduate physics classes. It is, of course, ironic to attribute a realist stance to a natural philosopher who by today's standards would have been labeled a positivist, as his oft-quoted remark that he was unwilling to feign any hypothesis suggests. Not many students would pick up on this, since physics courses generally lack any discussion of the different interpretative stances with regard to science. See Barad (1995, 2000) for the pedagogical implications of this widespread inattention to important metatheoretical issues.

12 The fact that light has momentum and energy is the basis for research projects

currently under way to build spacecraft that run on solar sails. Such craft would need no engines; they would sail around in space by using the light emitted by the sun to power and steer the craft much as a sailboat uses the wind.

13 More precisely, *quantum* means "a minimum amount of a physical quantity which can exist and by multiples of which changes in the quantity occur" (OED).

14 Planck's constant is a *very* small number: $h = 6.626 \times 10^{-34}$ joule-sec. Using some other natural constants it is possible to convert Planck's constant into a length—the Planck length. This length is so small that if you proposed to measure the diameter of an atom in Planck lengths and you counted off one Planck length per second, it would take you ten billion times the current age of the universe.

15 Actually, as we will see, Planck's constant marks something even more fundamental about nature. While it is sometimes said that the quantum is a measure of the graininess of nature, what is at issue is actually not a particular property of nature but the very nature of nature. The sense in which this discontinuity is an "essential" one is not that nature has a fixed essence, but that nature's lack of a fixed essence is essential to what it is. That is, as I will argue, nature is an intra-active becoming (where "intra-action" is not the classically comforting concept of "interaction" but rather entails the very disruption of the metaphysics of individualism that holds that there are discrete objects with inherent characteristics). See especially chapters 4 and 7. In a sense, this way of thinking about it honors the original name that physicists gave to this discontinuity—it was dubbed "the quantum of action" (although the term "action" has a particular technical meaning in physics that does not capture these nuances).

16 Quite atypical of the writings of theoretical physicists, Bohr's papers often include detailed drawings of experimental apparatuses. As Honner points out, "Bohr insisted on providing elaborate drawings of mechanical devices used for observing quantum events [in many of his discussions of complementarity], as if to emphasize the connection between descriptive concepts and classical apparatus" (Honner 1987, 119). For Bohr, meaning is necessarily tied to the world. It is important to note that Bohr is *not* making an operationalist claim. That is, he does not mean that a concept should be understood as being defined operationally in terms of how it is measured. Rather, Bohr is making a much more profound point about the nature of words and things. Bohr's point is at once semantic and ontological.

17 This is my rendering. Bohr does not state it in this way. See chapter 4 for further elaboration.

18 Bohr did not make any such explicit statement about how he theorizes the nature of the relationship between measurement and description, but I think this is a fair and illuminating statement. I will strengthen the nature of this mutual entailment hereafter in exploring important ontological dimensions of Bohr's account that were left implicit. It is unfortunate that Bohr did not directly discuss the important ontological dimensions of his account, since many misunderstandings and difficulties in reading Bohr can be traced to this lack of specificity in his ontological commitments. For more details, see the section hereafter entitled "A Bohrian Ontology."

19 For a detailed analysis of the time-of-flight measurement, see Barad 1995.

20 Or perhaps more to the point, the goal of this gedanken experiment is to examine Bohr's claim that measurement interactions are indeterminable, and so in any case we are not interested in the scenario where the size of the disturbance is negligible relative to the accuracy of our experiment. The same analysis applies in either case; it may just seem pedantic for a baseball.

21 The accuracy of the quantum theory is unparalleled. The agreement between the theoretical and experimental values of some physical quantities has been found to be accurate to ten decimal places. This is equivalent to getting the distance between New York and Los Angeles correct to within the thickness of a hair!

22 Some readers may be familiar with the fact that Newtonian physics is still used to calculate things like the trajectory of a rocket or a baseball. How is this possible when quantum physics has superseded Newtonian physics? What is the relationship between quantum mechanics and classical mechanics? Strictly speaking, Newtonian physics is a flawed theory, but it sometimes serves as a useful computational tool. This is because on a practical level there are some situations for which the equations of classical mechanics (i.e., Newton's equations) provide numerical values for some quantities that are excellent approximations to values calculated using the laws of quantum physics (i.e., the Schrödinger equation). And this is useful because the laws of classical mechanics are generally much easier to solve. The reason for this computational efficacy is the very small size of the quantum discontinuity. In particular, it's tiny in relation to the mass of an object such as a rocket or a baseball. When the mass (m) is large (relative to the size of h), the ratio h/m is very small, and the numerical values calculated using the laws of classical physics differ only slightly from the values calculated using the laws of quantum physics. Hence the claim that Newtonian physics "works" in the macroscopic domain must be understood with appropriate qualifications attached to "works." It "works" to the degree that the numerical values found by solving Newton's equations are adequate approximations for large-enough objects under certain situations. It doesn't mean that Newtonian physics strictly applies to such situations. Significantly, the values calculated using the laws of quantum physics and Newtonian physics will inevitably differ (because h is not zero), although they may be identical out to, say, six decimal places, but this fact will be evident if the calculation includes a sufficient number of decimal places (more than six, in this case). Hence, given laboratory equipment with sufficient accuracy (i.e., the ability to measure many decimal places), the limitations of the computational efficacy of Newton's equations will be exposed. This is often more than we can accomplish with current technologies, but it is simply a practical limitation. In other words, that Newton's equations (often) "work" when applied to macroscopic objects is not the same as saying that Newton's laws are the physical laws that govern the macroscopic world. The fact is—and this is the crucial fact—that no matter how small the ratio h/m is for any particular situation, it is never zero (which is precisely what classical physics assumes). The fact that h is very small explains why the quantum discontinuity went undiscovered for so long. The fact that h is *not* zero ($h \neq 0$), whatever its value, marks the existence of a fundamental discontinuity in the

natural world. Since Newtonian physics fails to take appropriate account of this discontinuity, it is, strictly speaking, a flawed physical theory.

23 The question will arise as to whether it is the picture that would be blurred or the actual object. Schrödinger raises this very issue in his famous paper about the cat paradox. See chapter 7 for a discussion of this point.

24 A tactile and intuitive sense of the measurement of momentum can be imagined as follows: think of catching a ball; the relative amount by which your arm moves back is an indication of the momentum of the ball. Note the importance of the catching arm's freedom of movement in sensing the ball's momentum.

25 There are actually many more than two options. We could use a semirigid support, in which case we would have semideterminate values for both the position and the momentum. Indeed, the more rigid the support, the more determinate is the position and the less determinate the momentum, and so on. The point is that over the full range of intermediary cases there inevitably is a reciprocal relation between the determinacy of the position and the momentum.

26 Along with Bohr I use the notion of a (quantum) phenomenon here in the technical sense specified by Bohr, which I will discuss shortly.

27 I have chosen to use this complex adjective instead of Bohr's term "arbitrary" for two reasons. First of all, "arbitrary" is misleading, since the cut is not totally arbitrary in that, according to Bohr, the cut must be made in such a way that the measuring device is macroscopic (this is necessary, since the use of classical concepts is predicated on a subject-object split—see discussion hereafter). Additionally, the term "arbitrary" carries misleading connotations such as the inappropriate associations of relativism. The point that I think Bohr seeks to emphasize in using the term "arbitrary" is that it stands in contrast to the classical inherent, fixed Cartesian subject-object distinction, and since this distinction isn't given, it must be constructed. Since for Bohr the apparatus constructs this distinction, I will use the terms "constructed" or "agentially enacted" or "agential" in the hope that these adjectives will connote the full complexity of its contingency. The contrast I want to emphasize is that while classical physics is premised on an inherent, fixed, unambiguous Cartesian distinction, quantum physics requires constructed, agentially enacted, materially conditioned, embodied, contingent Bohrian cuts. Bohr is appropriately positioned as Descartes's counterpart.

28 Heisenberg 1927, reprinted in Wheeler and Zurek 1983.

29 Bohr published a paper on complementarity in 1927 (reprinted in Bohr 1963a) in which he derives a set of relations that have the same form as the uncertainty relations derived by Heisenberg that same year. Although these relations have the same formal appearance, they do not have the same meaning (i.e., the symbols have different meanings), and therefore they are not the same relations. It is on this basis that I introduce the term "Bohr's indeterminacy relations" as an explicit parallel to "Heisenberg's uncertainty relations." For details of my argument, see chapter 7.

30 Unfortunately, in some discussions of quantum theory, the terms "uncertainty" and "indeterminacy" are used interchangeably, despite their different meanings. Throughout this book, I use these terms with distinctive meanings: while "uncertainty" refers to a lack of knowledge, "indeterminacy" refers to the state of being indeterminate (lacking definiteness). That is, uncertainty is an epistemic issue, while indeterminacy is an issue of ontology.

31 Recent experimental work on the foundations of quantum mechanics (e.g., Scully et al. 1991) gives empirical evidence in support of Bohr's interpretation over the uncertainty principle interpretation given by Heisenberg. See chapter 7.

32 Complementarity is Bohr's notion. Bohr proposed complementarity as an alternative epistemological framework to that of classical physics. Bohr commonly refers to complementarity as a "natural generalization of the classical mode of description" (Bohr 1963a [1927 essay], 56). "Complementarity" in this quote specifically refers to the mutual exclusivity of the definability of variables that are equally necessary from the point of view of classical mechanics (e.g., position and momentum). Note: There is a misconception that surfaces now and again that understands Bohr's complementarity as relying on Heisenberg's uncertainty principle for its enforcement. This is incorrect. Surely it doesn't make sense to see it that way if one understands that the two principles instantiate contrary philosophical views. See chapter 7 for further discussion.

33 As pointed out earlier, classical mechanics also holds that when you observe things, you disturb them. This accounts for its "obvious" intuitive appeal and all-too-popular and mistaken invocations of the uncertainty principle, as in "of course people will behave differently if you watch them." For example, consider the following statement offered on National Public Radio on October 6, 1993: "Corporate executives are like subatomic particles; their behavior changes when you observe them." The most surprising and troubling concern, of course, is the widespread misunderstanding among members of the physics community, not just the general public.

34 I offer this identification—"Bohr's indeterminacy principle"—by way of clarification in marking the crucial differences between Bohr's and Heisenberg's positions. This identification was (unfortunately) not used by Bohr, though it could have been very helpful in clarifying the issues. See chapter 7 for further discussion.

35 The notion of disturbance was never a central issue for Bohr. I disagree with some authors who claim that Bohr changed his philosophical position in response to the 1935 EPR paper. It is true that after 1935 Bohr was much more careful about his terminology, since he saw that certain words that he had used carried unwanted connotations that were the source of confusion. One term that Bohr recognized as having been particularly problematic is "disturbance," and he tried to be much more careful in his later writings to stay away from this potentially misleading term.

36 More precisely, Bohr used the term "phenomenon" in this specific sense in his later writings. In his earlier writings, he often used the term in its more colloquial sense. Once again, in the wake of the EPR paper, Bohr believed that his analysis was being misunderstood (e.g., he thought he had already addressed the issues that the EPR paper raised, a point that Bohr made quite explicitly in

his 1935 response), and he realized that the multiple connotations of terms and their inconsistent use contributed to the difficulties of communication. For further discussion, see chapter 7.

37 At least Bohr is quite specific in his use of this term in his later writings. "Bohr's provocative tendency, especially in earlier writings, to 'emphasize the subjective character of all experience' . . . brought his entire interpretation of quantum theory into peril" (Honner 1987, 65), parallel to terminological choices made by some science studies scholars early on that also proved to be rhetorically disadvantageous (which is not to deny the existence of other science studies scholars who in a principled fashion positioned themselves on the subjective side of the usual objective-subjective divide that is fundamentally being questioned).

38 See Daston 1999 on the history of "objectivity," and Lloyd 1996 on its multiple meanings.

39 It is not merely that the referent is changed but that in the context of his proto-performative formulation (and especially in my performative elaboration) referentiality must be (is) reconceptualized. See chapter 4.

40 See especially Folse 1985.

41 See Keller's "Anomaly of a Woman in Physics" (1977) for one personal account of a physics graduate school experience in the United States that is typical in its discouragement of reflexive (diffractive) thinking and contemplation of interpretative questions in physics. See Traweek (1988) as well.

42 Recent positivist readings of Bohr include Beller 1999, Fine 1986, and Cushing 1994.

43 See chapter 1 for a discussion of representationalism, which serves as the basis for traditionalist realist and antirealist stances.

44 It is interesting to see that in Bohr's case it was his realist commitments that led him to a failure of representationalism, in contrast to the commonly held contemporary view that postmodernist stances lead to the rejection of such staunchly held modernist principles (Rorty 1981). I will explain later how Bohr's realism is *not* inconsistent with his antirepresentationalism.

45 The important references are Einstein, Podolsky, and Rosen 1935 and Bohr 1935. See also the 1949 article by Bohr entitled "Discussion with Einstein on Epistemological Problems in Atomic Physics," published in a volume honoring the epoch-making contributions of his longtime friend Albert Einstein. In this article, Bohr quotes extensively from this particularly important passage of his 1935 paper (see Bohr 1949, 234). See chapter 7 for further discussion of the EPR paradox and Bohr's response.

46 When I originally came to this conclusion and wrote this section of my paper (Barad 1996a), I had not yet read Folse's 1989 article that considers Bohr's response to Einstein, Podolsky, and Rosen, and I was unaware that Folse also gives a positive reading of this passage (see Folse 1989, 259).

47 I have presented what may seem like a pedantic analysis of Bohr's use of the term "phenomenon" in this passage, but I do so because, as of 1935, his use of the term was still somewhat inconsistent, and it is therefore crucial to discern which usage is in play. (Bohr uses the term "phenomenon" colloquially in his earlier writings and with a very specific sense in his later writings.) In fact, as I argue here, this usage of the term is indeed consistent with the specific signification he assigns to it in his later writings. Upon careful examination, it becomes clear that Bohr's use of "phenomenon" to signify the wholeness in the interaction between "objects of investigation" and "agencies of observation," as was his specific practice in his later writings, is used in just this fashion throughout the article in question (Bohr 1935).

48 In my elaboration of Bohr's philosophy-physics, phenomena can be understood as quantum entanglements. Recent research on the foundations of quantum mechanics supports this understanding. See chapter 7.

49 I broaden this understanding of phenomena in my further elaboration of Bohr's philosophy-physics, moving it away from Bohr's restricted use of the term to specifically refer to measurements in a way that does not recognize other intra-actions. Granting phenomena ontological status makes this move possible.

50 This interpretation is consistent with the following point made by von Weizsäcker: "The fact that classical physics breaks down on the quantum level means that we cannot describe atoms as 'little things.' This does not seem to be very far from Mach's view that we should not invent 'things' behind the phenomena. But Bohr differs from Mach in maintaining that 'phenomena' are always 'phenomena involving things,' because otherwise the phenomena would not admit of the objectification without which there can be no science of them. For Bohr, the true role of things is that they are not 'behind' but 'in' phenomena" (quoted in Honner 1987, 15). Or as Honner puts it: "The term [phenomenon] was not intended to signify the uninterpreted appearance of the object of experience itself. Nor was Bohr trying to follow the Kantian distinction between the thing-in-itself and our perception of it. If one wanted to talk about such 'things,' then they were as Weizsäcker put it, to be found *in* the phenomena rather than behind it" (Honner 1987, 68). The nature of this relationship is a point of contention among Bohr scholars. My own studies of Bohr's writings brought me to a conclusion similar to von Weizsäcker's before I began reading the secondary texts, and in spite of subsequent readings of the many different interpretations offered, it has always seemed very clear to me that Bohr's notion of phenomenon is definitely not that of Kant and indeed does not refer to mere appearances in contrast to the thing-in-itself. The point is that phenomena constitute a nondualistic whole, so that it makes no sense to talk about independently existing things as somehow behind or as the causes of phenomena, contra Folse's reading (see especially Folse 1989, 265). As I will argue later, a determinate causal structure does not preexist phenomena, so it is meaningless to identify objects as the causes behind phenomena.

51 See chapter 7 for more details concerning this question of the objective referent.

52 The positions that Heisenberg and Dirac articulate here are consistent with Heisenberg's instrumentalist leanings and Dirac's traditional realist leanings.

FOUR • AGENTIAL REALISM

1 Dissatisfaction is explicit in the literature of the 1980s. See, for example, Haraway's "Gender for a Marxist Dictionary: The Sexual Politics of a Word" (published in 1987) and "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective" (published in 1988), both reprinted in Haraway 1991. See also Butler 1989.

2 Which is not to dismiss valid concerns about specific accounts of performativity that grant too much power to language. Rather, the point is that this is not an inherent feature of performativity but an ironic malady.

3 It would be surprising if my own attempt at making a successful ionizing "quantum leap" out of the humanist-representationalist orbit doesn't fall prey to the same pull, snagged by some component or another, so great is this force. My hope, nonetheless, is that this endeavor may yet produce new possibilities that reconfigure the range of possible new attempts. And that may well have made it worthwhile.

4 Both poststructuralists and science studies scholars have expressed interest in and proposed performative approaches to alternatives to representationalism. See chapter 1 for a more detailed discussion of these different approaches.

5 Representationalism may fancy telescopes and microscopes as pure instruments of reflection, but the fact is that diffraction matters for telescopes and microscopes (even optical ones).

6 "Posthumanism" has multiple valences in the literature. "Transhumanism" or "antihumanism" or "metahumanism" might have been better options for my purposes in some ways, but each has its own difficulties, as well. For example, "transhumanism" has already been appropriated for unreflective technophilic purposes and suggests a transcendent position. And "antihumanism" has been used by some poststructuralists who nonetheless take the boundary between nature and culture, the human and the nonhuman, to be a given; for these critics, the social arena of human interactions is what matters. I have chosen "posthumanism" because I am interested in contesting this most widely used term, especially as it engages questions of technoscience. Also, I want to make clear that my interest is in thinking about the limits of humanism, and hence I use the term "posthumanism" to indicate this critical engagement; this should not be taken to mean that I advocate positions that use the notion of the posthuman as the next stage of the human, as if it no longer makes sense to talk about the human.

7 Nor was it ever the issue for Haraway, though some have unfortunately misread her "Cyborg Manifesto" in this way.

8 It is worth remembering that the line between the physical and the metaphysical is not a natural, permanent delineation (see chapter 7 on the new experimental metaphysics).

9 Atomism is said to have originated with Leucippus and was further elaborated by Democritus, a devotee of democracy, who also explored democracy's anthropological and ethical implications. Democritus's atomic theory is often identified as the most mature pre-Socratic philosophy, directly influencing Plato and Epicurus, who transmitted it into the early modern period. Atomic theory is said to form the cornerstone of modern science.

10 See chapter 3.

11 Some philosophers may see the move I am making as naturalistic. I have labeled this approach "posthumanist" rather than "naturalist" because the considerations that go by the former term are also interested in troubling the nature-culture distinction (though it is important to recognize that there are many different posthumanisms), whereas "naturalism" (which also designates multiple stances) generally holds the nature-culture dualism in place. Rather than presuming an inherent distinction between nature and culture, I am interested in accounting for how this distinction is made and remade. See Rouse 2004a on understanding agential realism as a form of naturalism that does not abide by the nature-culture dualism.

12 Causality from an agential realist perspective is discussed hereafter.

13 Bohr argues on the basis of this single crucial insight, together with the empirical finding of an inherent discontinuity in measurement intra-actions, that one must reject the presumed inherent separability of observer and observed, knower and known. See chapter 3.

14 That is, relations are not secondarily derived from independently existing relata; rather, the mutual ontological dependence of relata—the relation—is the ontological primitive. As discussed later, relata only exist *within* phenomena as a result of specific intra-actions (i.e., there are no independent relata, only relata-within-relations). The term "intra-action" signifies *the mutual constitution of relata within phenomena* (in contrast to "interaction," which assumes the prior existence of distinct entities). In particular, the different agencies remain entangled.

15 The phrase "any old playing around" is a reference to Schrödinger's expressed concern that the notion of measurement retain some sensible meaning even if the properties expressed do not preexist the measurement process: "In general, a variable *has* no definite value before I measure it; then measuring it does *not* mean ascertaining the value that it *has*. But then what does it mean? There must still be some criterion as to whether a measurement is true or false, a method is good or bad, accurate, or inaccurate—whether it deserves the name of measurement process at all. Any old playing around with an indicating instrument in the vicinity of another body, whereby at any old time one then takes a reading, can hardly be called a measurement of this body" (Schrödinger 1935, 158). See chapter 7 for more details.

16 In *How Scientific Practices Matter*, Rouse takes up my notion of causal intra-actions and situates Bohr's analysis in terms of philosophical debates about causation.

17 For a discussion of the nature of the role of the experimenter and other human subjects, see hereafter.

18 Because phenomena constitute the ontologically smallest unit, it makes no sense to talk about independently existing things as somehow behind or as the causes of phenomena. In a sense, there are no noumena, only phenomena. Agential realist phenomena are not Kantian phenomena or the phenomenologist's phenomena.

19 The metaphor of "flow" is used here to conjure the idea of agency as an enact-

ment, as opposed to its more usual conception as a property of entities (most commonly humans). On the other hand, it is also misleading in that this metaphor connotes a sense of fluidity that is premised on dynamics that change continuously in time, whereas intra-actions take place not in space and time (as if they were containers or markers of what already is) but in the making/marking of spacetime. Crucially, this profound shift goes beyond the usual geometrical concepts of dynamics to a reconceptualization of "dynamics" itself where continuity is not assumed and topological shifts (e.g., changes in continuity, boundedness, etc.) may be of great significance.

20 See chapter 3 for more details.

21 This can perhaps be likened to the mistaken belief that cookbook laboratory exercises teach students about experimentation. They don't. Rather, at best they are heuristic devices for learning theoretical notions, but even this is questionable (see Barad 2000b).

22 The recent shift in focus from the study of scientific knowledge to the study of scientific practice has contributed to the acknowledgment of the complexity of experimentation. See, for example, Hacking 1982, 1983; Galison 1987, 1997; Pickering 1984.

23 See chapters 1 and 5 for more details.

24 I am concerned here with the Foucauldian notion of discourse (discursive practices), not formalist and empirical approaches stemming from Anglo-American linguistics, sociolinguistics, and sociology.

25 Foucault makes a distinction between "discursive" and "nondiscursive" practices, where the latter category seems to be reduced to social institutional practices: "The term 'institution' is generally applied to every kind of more-or-less constrained behaviour, everything which functions in a society as a system of constraint and which isn't utterance, in short, *all the field of the non-discursive social, is an institution*" (Foucault 1980, 197–98; italics mine). This specific social science demarcation is not particularly illuminating in the case of agential realism's posthumanist account, which is not limited to the realm of the social. In fact, it makes no sense to speak of the "nondiscursive," per se, given my posthumanist conception of discursive practices as boundary reconfigurings that are inherently material and need no material support.

26 Which is not to suggest that meaning is ever fixed once and for all. Discursive practices entail ongoing contestations and re(con)figurings. (Nor is it to suggest that all meanings are set are once—recall Bohr's point about complementary conditions for meaning making.) Ambiguities always exist.

27 See the description of the brittle star in chapter 8.

28 For more details, see chapter 1.

29 See discussion in chapter 1.

30 Derrida's term "historiality" rather than "historicity" is perhaps more appropriate. See the following section on re(con)figuring spacetimematter.

31 For further discussion, see chapters 5 and 6.

32 Referentiality is reconceptualized. Words do not refer to things as in representationalist accounts. Rather, words and things are intra-actively coarticulated through specific patterns of practice. The world differentially articulates itself. To speak of the "objective referent" is not to presume to put into relation disparate entities (i.e., words and things or words and phenomena) but to acknowledge the relationality of the intra-active coarticulation of matter-discourse. Rouse (2002) calls this an expressivist account: "The material-inferential relations between patterns of talk and particular practical interactions (including experimental practices) both articulate the meaning or content of what is said and express what is going on in the practical interactions. In the case of experimental science, I will argue, this expressive role of scientific discourse is not something external to the phenomena investigated, but is a constitutive component of the phenomenon itself" (269). Kirby (1997) puts it this way: "What I am trying to conjure here is some 'sense' that word and flesh are utterly implicated, not because 'flesh' is actually a word that mediates the fact of what is being referred to, but because the entity of a word, the identity of a sign, the system of language, and the domain of culture—none of these are autonomously enclosed upon themselves. Rather they are all emergent within a force field of differentiations that has no exteriority in any final sense" (126–27).

33 The analogy between this example and the complementarity of position and momentum measurements is not very subtle. Recall that the measurement of position requires a rigid measuring apparatus and the measurement of momentum requires one with movable parts.

34 Although it might be interesting to contemplate an agential realist post-phenomenological elaboration of lived bodily experience, Bohr's focus, at least, is not on bodily experience per se.

35 The literature on the question of bodily boundaries and the nature of embodiment is vast. In what follows, I present only the barest outline of a very small fraction of the research on this rich topic.

36 The picture in chapter 2 showing the diffraction patterns around the edges of a razor blade (figure 2) nicely illustrates the indeterminacy of bodily boundaries. For a discussion of diffraction, including the bending of light around the edges of objects, see chapter 2.

37 These examples also bring to mind the question of the nature of "seeing" atoms discussed at length in chapters 1 and 8.

38 Merleau-Ponty and Bohr use nearly the same example of a visually challenged man with a stick to make different points. In contrast to Bohr's focus on the mutual exclusivity of different cuts differentiating subject from object, Merleau-Ponty uses this example to illustrate the spatiality of the body in its becoming through bodily action. For Merleau-Ponty, this bodily possession of space, the spatial existence of the human body, is "the primary condition of all living perception" (1962, 109). It is interesting to think about their respective considerations together, but one must be careful not to elide important differences between them. In particular, one must remember *not* to read Bohr's emphasis on phenomena as phenomenological.

The nature of the embodiment in the two cases is not, strictly speaking, identical, although there are few clues in the respective reports that indicate any qualitative difference. In the example that Bohr considers, the person is not blind but is trying to negotiate his way in a dark room. And although Merleau-Ponty doesn't discuss the issue directly, "cane traveling" is not simply a matter of picking up a stick; it is a skillful practice that has to be learned. There is, indeed, an acknowledgment that "habit" plays an important role in our sense of "being-in-the-world."

39 This discussion hints at some of the ethical implications discussed in more detail in chapter 8. Note that the very notions of consciousness, knowing, and lived experience are reworked.

40 Allucquére Rosanne Stone, "Split Subjects, Not Atoms; or How I Fell in Love with My Prosthesis" (paper presented at the 1994 Located Knowledges Conference).

41 Haraway 1994, 67. That is, Haraway's approach and theorization of "situatedness" differs in important ways from traditional phenomenological approaches. On Haraway's notions of "situatedness" and "location," see also chapter 8, note 45.

42 The subject cannot fully characterize itself without splitting. Or perhaps more to the point, the world can never characterize itself in its entirety; it is only through different enactments of agential cuts, different differences, that it can come to know different aspects of "itself." Only part of the world can be made intelligible to itself at a time, because the other part of the world has to be the part that it makes a difference to. See hereafter and chapter 7 for further discussion.

43 The title of this section playfully winks at Magritte's famous painting *Ceci n'est pas une pipe*, which directly challenges representationalism. See Foucault's *This Is Not a Pipe* (1983) for an interesting engagement between Foucault and Magritte concerning the limits of representationalism.

44 Quoted in Friedrich and Herschbach 1998, 174.

45 In spite of its widespread colloquial use to mark a large leap forward, a "quantum leap" is actually very small. The important point about a quantum leap is not its size but the fact that an object disappears from one place and winds up in another without being at any point in between. For example, electrons are only ever found in one of the discrete orbitals, not in spaces between orbitals.

46 Einstein won the Nobel Prize not for the theory of relativity, as many people believe, but for his explanation of the photoelectric effect: Einstein insisted that the postulation of a particle-like notion of light—the photon—was necessary to account for the photoelectric effect. However, Einstein's explanation turns out not to be accurate: "Textbooks regularly repeat Einstein's arguments as proof that light possesses a particle nature. And yet, ironically it has been cogently argued that Einstein's conclusions were not fully justified. . . . In 1969, Jaynes and Lamb and Scully showed that one can account for the photoelectric effect without recourse to the concept of a photon at all" (Greenstein and Zajonc 1997, 23). See chapter 2 of Greenstein and Zajonc 1997 for further details.

47 Stern was taken aback by Bohr's model of the atom: "Shortly after it appeared in mid-1913, Stern and his colleague Max von Laue made an earnest vow: 'If this nonsense of Bohr should in the end prove to be right, we will quit physics!' " (Friedrich and Herschbach, 2003). In the end, Stern confessed, " 'Bohr is right after all.' Gerlach also sent a postcard to Bohr with a congratulatory message, showing a photograph of the clearly resolved splitting" (ibid.). The Bohr model was superseded by the new quantum theory. Even theories that prove to be incorrect and models that are limited in important ways or misinterpretations of confirmed theories can be productive.

48 "After Goldman's cheque had saved our experiments, the work [on the Stern-Gerlach experiment] went on successfully" (Max Born, quoted in Friedrich and Herschbach 1998, 180).

49 Friedrich and Herschbach (2003) reenacted the original experiment and found that the image did not appear when breathed on; rather, it was the actual smoke from the cigar that did the trick. However, they did not mention if Herschbach (who played Stern for the reenactment) is a longtime smoker of cigars and how cheap the cigar was. It seems plausible at least that Stern's breath was significantly more sulfuric than Herschbach's. That is, the historiality of Stern's bodily materiality might have been a relevant factor in the materialization of the evidentiary traces. In other words, reproducibility is not a trivial matter: in particular, it requires a full accounting of all the relevant features. (The occasion for the reenactment was the dedication of a new center for experimental physics at the University of Frankfurt named for Stern and Gerlach.)

50 The lesser salary of an assistant professor accounted for the cheap cigars that Stern was smoking at the time, at least as he tells it. Stern came from a privileged background. His affluent parents worked the old boys' network to gain Stern a postdoctoral position under Einstein. It was Einstein who turned Stern's attention to quantum phenomena.

51 Mirrors are generally made of glass with a silver (or silver amalgam) coating on one side. For more examples of the practical scientific consequences of the indeterminacy of the outside boundary of the apparatus, see chapter 7. (Many of the new quantum optics experiments discussed there deploy mirrors quite strategically.) It may be useful to contrast the complexity of the apparatus as presented in this section with textbook representations of the Stern-Gerlach apparatus (especially the "stripped down" models often used in discussions of spin in quantum physics—see, for example, the discussion in chapter 7).

52 See A. Franklin 2002 and Friedrich and Herschbach 2003 for further details of what this splitting did and didn't confirm at different moments of time as changes in the theory took place. Science is not a simple matter of confirming hypotheses or theoretical predictions by testing them against experiments. See, for example, Hacking (1983) and Galison (1987, 1997).

53 In their earlier article on the Stern-Gerlach experiment, Friedrich and Herschbach (1998) attribute conspiratorial intentions to nature ("an uncanny conspiracy of Nature"). In their later article (2003), nature is "duplicitous" and (once again) "uncanny" (unnatural?!). These are curious conclusions to draw about Stern and Gerlach's complex intra-actions with nature. It seems as if the authors could just as easily (if not more justifiably) have paid homage to nature for being so remarkably cooperative in presenting a productive coincidence rather than a

null result. It's interesting to contrast these attributions with Haraway's remark that "the world is a coding trickster with whom we must learn to converse" (Haraway 1991, 201). Each of these attributions seeks to recognize nature's agency in some way—a noble and important goal—but the different natures ascribed to nature speak volumes.

54 This metaphorical reading is Friedrich and Herschbach's (2003). See the article for a picture of the plaque.

55 Neither Gerlach nor Heisenberg joined the Nazi Party, and both resisted attacks on Einstein and "Jewish science." For more details on Gerlach's role in the German effort to produce an atomic bomb during World War II, see Cassidy 1992.

56 See Butler's theory of gender performativity. Especially important here is the fact that gender is *not* what one is or a characteristic that one has or a performance that one chooses to engage in.

57 See chapter 7.

58 See chapter 1.

59 There are many critiques of the spectator theory of knowledge. In chapter 7, I consider the difficulties this presupposition poses for cosmological theories.

60 Latour also emphasizes the important point that "laboratories have no outside" (Latour 1983, 267).

61 For a posthumanist poststructuralist reconceptualization of the notion of "social structures," see chapter 6.

62 The nature of causal intra-actions is discussed in detail in the next section.

63 Not even space itself can be understood as a mere container for matter. See hereafter.

64 Rouse (2002) makes a similar point in reconceptualizing measurements as causal intra-actions: "Part of the point of initially conceiving experimental practices as *causal* interactions is to insist that it is not through the intentions of scientists or their deliberative performances in constructing an experiment that discursive practices and causal interactions are mutually implicated. Most philosophical discussions of causality take the boundaries of causally interacting systems (objects or events) to be already determinate, without asking how such determination occurs. The point of my argument is to show that this presumption is illegitimate" (270). Indeed, Rouse reconceptualizes intentionality in terms of causal intra-actions: "Intentional interpretation itself is an example of material intra-action on my account (just as any good naturalist would expect!)" (285). I am indebted to Rouse for illuminating discussions on this and related points.

65 Apparatuses may (but need not) include both humans and nonhumans. In any case, apparatuses are not to be understood as assemblages of preexisting, separately determinate individuals of one kind or another.

66 For a detailed discussion of the EPR challenge, see chapter 7. See also chapter 3.

67 For further discussion of this issue, see chapter 7.

68 See Howard 1997 for more details.

69 For further discussion of this important point, see chapter 7.

70 The experiments need not be reproduced, per se; they just need to be *reproducible.* What is at issue for Bohr is the possibility of reconstructing the same experimental arrangement, which reproduces the same constructed cut between the observed object and the agencies of observation, that is, the same phenomenon. For further discussion of this point, see Barad 1996b, 192n35. Rouse also offers a similar clarification: "That a particular intra-action is causal indicates that under the circumstances its pattern would recur, but there need be no actual regularity that it instantiates. . . . A causal intra-action has not been correctly specified without the shielding that effects its bounds. To repeat the crucial point: causal intra-actions must be in principle *reproducible* and unambiguously *specifiable*, but their actual reproduction or descriptive specification is neither part of nor necessary for their occurrence" (Rouse 2002, 280–81). Rouse (2002) uses the notions of intra-activity and reproducibility to argue for the normativity of nature.

71 Indeed, the key passage of Bohr's response to the EPR challenge quoted earlier suggests that what is at issue for Bohr is the objective resolution of the inherent ambiguity between object and agencies of observation—that is, the cut.

72 For a more detailed discussion of these crucial points, see chapter 7. Bohr meets the challenge that he sets for himself in a remarkable and beautiful way. In a sense, the fullness of what he achieves can be appreciated only if one gets into a detailed discussion of his insistence on the necessity of using classical concepts for the unambiguous description of phenomena. But that requires a lengthy discussion that is unnecessary here. Nonetheless I suspect that it may enhance some readers' understanding if at least some sense of the deeper issues is presented here. So here it is in brief. Why does Bohr insist on the necessity of using classical concepts? Implicit in our classical descriptive concepts is an inherent subject-object distinction, and since phenomena entail the placement of a Bohrian cut delineating a subject-object distinction, it is consistent to use classical concepts to describe phenomena. But Bohr strengthens the claim for the appropriateness of our use of classical concepts to describe phenomena to one of necessity. In Bohr's account, the apparatus that gives definition to particular classical concepts to the exclusion of others *and* enacts a Bohrian cut between subject and object specifies the relationship between classical descriptive concepts and phenomena: since by their very definition classical descriptive concepts entail a particular subject-object distinction (this is what it means to be "classical") as specified by the circumstances required for their measurement, and since phenomena include a subject-object distinction enacted by said circumstances (namely, the one in question that gives definition to a particular classical concept), it follows that these particular classical concepts are just the ones that are given determinate meaning and hence can be used in describing phenomena. That is, phenomena are necessarily described using concepts conditioned by particular subject-object distinctions.

73 In doing so, my agential realist elaboration is able to solve some of the most stubborn difficulties that Bohr's account faces in confronting the interpretative issues in quantum mechanics. See chapter 7 for an agential realist interpretation of quantum mechanics.

74 Once again the contrast I want to emphasize is that while classical physics is premised on an inherent distinction between subject and object (i.e., a fixed, universal, Cartesian cut), quantum physics relies on agentially enacted cuts.

75 I am grateful to Joe Rouse for putting this point so elegantly (private conversation). See Rouse 2002 for an extensive discussion of traditional conceptions of causality and a rethinking of causality in terms of intra-actions. Rouse suggests that "measurement" need not be a term about laboratory operations, that before answering whether or not something is a measurement, a prior question must be considered, namely, what constitutes a measurement of what?

76 Intelligibility is not a human-based affair. It is a matter of differential articulations and differential responsiveness or engagement. See chapter 8. Vicki Kirby (1997) makes a similar point.

77 Butler (1993) also rejects both these options, proposing an alternative that she calls the "constitutive outside." Butler describes the constitutive outside as the "that which" to which language is impelled to respond in the repeated attempt to capture the persistent loss or absence of that which cannot be captured. It is this persistent demand for, and inevitable failure of, language to resolve that demand which opens up a space for resignification—a form of agency—within the terms of that reiteration. In Butler's account, the "constitutive outside" is an exteriority defining the limits of the domain of human-based discursive practices.

78 Geometry is concerned with shapes and sizes (this is true even of the non-Euclidean varieties, such as geometries built on curved surfaces like spheres rather than on flat planes), whereas topology investigates questions of connectivity and boundaries. Although spatiality is often thought of geometrically, particularly in terms of the characteristics of enclosures (like size and shape), this is only one way of thinking about space. Topological features of manifolds can be extremely important. For example, two points that seem far apart when viewed geometrically may, given a particular connectivity of the manifold, be understood as being proximate to each other (as, for example, in the case of cosmological objects called "wormholes") when topological considerations are taken into account.

79 This is true at the atomic level, as well. Indeed, as Bohr emphasizes, the mutual exclusivity of position and momentum is what makes the notion of causality in quantum physics profoundly different from the deterministic sense of causality of classical Newtonian physics. In particular, as Bohr points out, specific material conditions have to exist for the concept of position to be meaningful, and if such conditions exist, they materially exclude the notion of momentum from being intelligible. Hence the mutual exclusivity of position and momentum—the two quantities that Newtonian mechanics enlists in specifying deterministic trajectories—represents a failure of the Newtonian framework along with its traditional notions of trajectory and causality.

80 The real is not constituted by a collapse of the existing set of possibilities; it is not a singular selection among present alternative possibilities (see chapter 7). In this regard, Deleuze's critique, which rejects talk of the real and the possible for the actual and the virtual, trivializes the set of possible relationships between the real and the possible. In any case, Deleuze doesn't use these terms in the way they are used here and his critique is irrelevant in this sense.

81 This new sense of aliveness applies to the inanimate as well as the animate, or rather, it is what makes possible the very distinction between the animate and the inanimate.

82 Twentieth-century physics has had much to say about the nature of space and time. Newton's absolute conception of time as a series of moments evenly spaced along a line that goes to infinity in both directions is found to be wanting in Einstein's hands; the same is true for his absolute conception of space which is assumed to be uniform and unchanging, a container that marks place but is itself unmarked. According to Einstein, time is relative to motion (not the reverse): "time," by definition, is what is measured by an observer's clock, and analogously, "space," by definition, is what is measured by an observer's ruler. And what an observer measures with a clock (ruler) differs for differently moving observers: time (space) is relative to the motion of an observer. (See Galison 2003 for an account of the multiple apparatuses that contribute to Einstein's development of the special theory of relativity, including clocks, patents, trains, commerce, telegraphy, and colonial conquest.)

Although both quantum mechanics and the theory of relativity offer profound challenges to Newtonian physics and its philosophical worldview, they do so in very different ways. On the surface at least, they seem to target the same issues: both seem to insist on a significant role for the observer and on the relative nature of measured values, in marked contrast to Newtonian physics. However, the two theories understand the nature of observation and the role of the observer very differently. While Einstein presumes that observer and observed are distinct states with separately determinate boundaries and attributes, Bohr argues that quantum physics challenges these ontological assumptions and their epistemological implications. That is, Einstein presumes the separately determinate nature of objects and observers, while Bohr questions this presupposition.When Einstein says that time is relative, he means that it is not possible to give an absolute specification of time, independently of the motion of the observer; he is not denying the existence of separately determinate states for the observer and the observed. That is, while Einstein insists on the *relative* nature of space and time, Bohr challenges the conception of the observer in classical physics and argues for the *relational* nature of the measurement process.

According to the special theory of relativity, time is but a fourth spatial dimension, and the usual couple "space and time" becomes the single term "space-time." The special theory of relativity describes the motion of objects relative to inertial (i.e., nonaccelerating or constant velocity) frames of reference (i.e., the combination of observer, clock, and coordinate grid), whereas the general theory of relativity takes account of noninertia frames of reference. General relativity is a theory of dynamical space-time relations. It is a field theory (rather than an action-at-a-distance theory like Newton's) that accounts for the gravitational force in terms of the curvature of space-time. It is the successor to Newton's theory of gravity. In Einstein's account, the structure of space-time depends on the distribution of matter in the universe. Despite this coupling of matter to space-time, the general theory of relativity does not challenge the Newtonian understanding of matter as substances made up of discrete entities with inherent properties. In an important sense, both the special and general theories of relativity are a part of classical physics.

83 Although theories of emergence also involve nonlinear dynamics, this is not what is implied here, if by "emergence" one means a nonlinear interaction that externalizes time. I am grateful to Astrid Schrader for bringing this point to my attention.

84 Derrida's (1976) notion of "historiality" may be a more appropriate term than the more usual "historicity," since it connotes the important idea that time is an operator, not a parameter. I do not insist on it throughout owing to its unfamiliarity, but it is implied from here on out; I use it in this section because it is important to explicitly displace the more usual sense of time.

Rheinberger, following Derrida, contrasts "historiality" with "history": "From a historial point of view, we also have to presume that recurrence, in terms of rearrangements and reorientation, is at work as part of the time structure of the innermost differential activity of the systems" (Rheinberger 1997, 178). Similarly, see Butler's distinction, following Derrida, between iterability and repetition: "Significantly, the Derridean analysis of iterability is to be distinguished from simple repetition in which the distances between temporal 'moments' are treated as uniform in their spatial extension. The 'betweenness' that differentiates 'moments' of time is not one that can, within Derridean terms, be spatialized or bounded as an identifiable object. It is the nonthematizable différance which erodes and contests any and all claims to discrete identity, including the discrete identity of the 'moment.' What differentiates moments is not a spatially extended duration, for if it were, it would also count as a 'moment,' and so fail to account for what falls between moments. This 'entre,' that which is at once 'between' and 'outside,' is something like nonthematizable space and nonthematizable time as they converge" (1993, 245). See also Kirby 1997, esp. 121–23; and Rouse (2006).

While the idea that time may be an operator rather than a parameter has been made famous by Prigogine's uptake of this notion into the subject matter of far-from-equilibrium thermodynamics, the question of time's status as an operator was raised decades earlier by theoretical physicists developing quantum mechanics. The question in this context had to do with the asymmetry inherent in the energy-time versus position-momentum uncertainty relations. While each of the other variables in these relations is an operator—in particular, a Hermitian operator and therefore an observable—the question arose as to whether time could be understood as an operator as well. In 1933, Pauli produced a theorem that suggested that it is not possible to posit time as a self-adjunct operator in a way that is consistent with the other important results of quantum theory, but contemporary physics research has called this theorem into question. Some of the recent investigations cite von Neumann's concern: "First of all we must admit that this objection [time being just a number] points at an essential weakness which is, in fact, the chief weakness of quantum mechanics. In fact, while all other quantities are represented by operators, there corresponds to time an ordinary number-parameter t, just as in classical mechanics" (Galapon 2005, 1).

85 The metaphor of tree rings is meant to be evocative of the sedimenting materiality of an ongoing process of becoming; I hope that it will be taken in this spirit, and not as some reified imagining. The complexity of the topological dynamism of mattering doesn't come through in this metaphor. Another metaphor may do a bit better, but again I don't intend to capture an idea but to evoke further thought: Imagine putting drops of colored dyes into a piece of bread dough. As you knead the dough, the dyes spread out in different patterns of entangled lines and surfaces. But this process is too tame as well, since the changes are all continuous and the dough maintains its topology. So break off some pieces and reattach them to different areas and continue kneading. Take a different kind of dough and make a different manifold with different lines, surfaces, and volumes of color. Intermingle the dough pieces: new entanglements form, new possibilities emerge. This metaphor still doesn't cut it; the motion seems to come from the outside, the indeterminacies don't appear to be evident, the possibilities come across as less lively, fresh, and exuberant than they are. Instead of dough, consider . . . other possibilities . . . in an unending iterative process of enfolding.

86 A common point of departure for Judith Butler and Niels Bohr is the fact that exclusions constitute the defining limit of the domain of intelligibility. For Butler, the domain of abject beings forms the constitutive outside of the domain of intelligibility: "This exclusionary matrix by which subjects are formed thus requires the simultaneous production of a domain of abject beings, those who are not yet 'subjects,' but who form the constitutive outside to the domain of the subject. The abject designates here precisely those 'unlivable' and 'uninhabitable' zones of social life which are nevertheless densely populated by those who do not enjoy the status of the subject, but whose living under the sign of the 'unlivable' is required to circumscribe the domain of the subject" (Butler 1993, 3). For both theorists, exclusions are a constitutive element of boundary-drawing practices.

87 For further discussion, see chapter 8.

88 There are numerous critiques of the spectator theory of knowledge. Some of the most relevant to the discussion here include Haraway 1988; Kirby 1997; Rouse 2002; and Bohr 1963a, 1963b, 1963c. For a cosmological critique, see Smolin 2001 and further discussion in chapter 7.

89 The notion of agential separability, which is predicated on the agential realist notion of intra-actions, has far-reaching consequences. Indeed, it can be shown to play a critical role in resolving the "measurement problem" and other long-standing problems in quantum theory. See chapter 7. It also has profound ethical and epistemological implications. See chapter 8.

90 Vicki Kirby, private communication, 2002. Kirby's sustained interrogation of the tenacious nature-culture binary is unparalleled. See Kirby 1997 for a remarkable "materialist" (my description) reading of Derrida's theory.

FIVE • GETTING REAL

1 This chapter was originally published as Barad 1998c. The structure of the original article is maintained here even though the development of agential realism is covered in greater depth in the previous chapters. In this way, the chapter retains its original form as an autonomous text suitable for classroom use or other forums for discussion. At the same time, this chapter offers a useful example of the application of agential realism. The reader who has read chapters 3 and 4 may want to skim the parts of sections that repeat points made in these chapters and read only the parts related to the specific example at hand. Some readers of the manuscript appreciated reading a condensed version of the material previously covered and thought this presentation would be especially useful for teaching undergraduates.

The present chapter focuses on observation practices. However, one should not infer from this that agential realism applies only to human-based practices (a point I've emphasized in chapter 4). On the contrary, it is important to note that agential realism is a framework that provides a general account of material-discursive practices, including practices that are not human based. In fact, the careful reader will note that in the agential realist analysis of new reproductive technologies considered here, a crucial component of the analysis offered is an understanding of the practices by which the "human" is differentially constituted. Indeed, the contributing factors include practices that are not usually understood as human based and forms of agency that lie beyond the usual human-centered considerations.

2 See chapter 4 for a detailed explication of the agential realist understanding of discursive practices (particularly relevant for this chapter is its posthumanist elaboration of the Foucauldian notion of discursive practices).

3 For further discussion, see chapter 4.

4 I am referring here to the Foucauldian notion of "discursive practices" that Butler uses, not my posthumanist agential realist conception (see chapter 4).

5 This section summarizes some key points in chapter 3. Readers who have already read chapter 3 may want to skip this section.

6 For a discussion of the methodology of diffractive readings, see chapter 2. It is Bohr's general epistemological framework, not his interpretation of quantum mechanics per se, that is of interest here. It is important to note that Bohr did not see the epistemological (or ontological) issues with which he was concerned as being circumscribed by the size of Planck's constant; in particular, to his thinking the profound epistemological and ontological shifts that are entailed are not applicable solely to the microscopic realm. (Most physicists understand quantum mechanics to be the best physical theory we have. Quantum physics supersedes Newtonian physics. It is not the case, as far as we know, that there is an abrupt change in physical laws as one proceeds from the microscopic realm to the macrosopic one.) In fact, Bohr insisted that if Planck's constant had been larger, the epistemological issues that concerned him would simply have been more evident, and we would not have been as inclined to be fooled into representationalism. In this regard, I want to emphasize that my approach does *not* rest on mere analogies between the microscopic and macroscopic domains. Rather, my approach is to examine and further elaborate Bohr's insights concerning widely applicable philosophical issues such as the conditions for objectivity, the appropriate referent for empirical attributes, the role of natural as well as cultural factors in scientific knowledge production, and the efficacy of science (especially in the face of increasingly numerous and sophisticated demonstrations of its contingent nature). See chapter 2 for more details.

7 This is my rendering. Bohr does not state it in this way, but I think it is a particularly useful way to state his point. I have argued that this specific rendering of concepts as specific material arrangements is consistent with Bohr's philosophical framework. See chapter 3 for more details.

8 For a detailed analysis, see chapter 3. "Agencies of observation" is Bohr's term, which he seems to use interchangeably with "apparatus." Because of the usual association of agency with subjectivity, "agencies of observation" hints at an ambiguity in what precisely constitutes an apparatus for Bohr. For further discussion, see the section "On Apparatuses" hereafter and chapter 4 for a more complete discussion.

9 Since "wholeness" takes on a particular set of connotations within feminist theory, it may be worth mentioning some of the ways in which "wholeness" is being reconceptualized here: Wholeness, in this account, does not signify the dissolution of boundaries. Wholeness is not about prioritizing the whole over the sum of the parts; wholeness signifies the inseparability of "component" parts of phenomena (i.e., the ontological primacy of relations over relata). Wholeness requires that delineations, differentiations, and distinctions be drawn; differentness is required of wholeness. Utopian dreams of dissolving boundaries are pure illusion, since reality is (iteratively) (re)constituted through the (re)making of boundaries. See chapter 4.

10 Bohr, quoted in Folse 1985, 124.

11 Bohr called this cut "arbitrary" to distinguish it from an "inherent" cut. But the cut is not completely arbitrary, and so I use "constructed" as a contrast to "inherent" (see chapter 3).

12 Bohr's *epistemic* notion of objectivity is not the only possible conception that is consistent with Bohr's framework. See chapter 4 for an *ontic* ("ontoepistemic") conception of objectivity that strengthens Bohr's philosophy-physics, removing some of its most objectionable humanist underpinnings.

13 "Intra-action" is my term, not Bohr's. See chapter 4 for my posthumanist performative elaboration of Bohr's epistemological framework and for a more detailed discussion of "intra-action." It is important to note that intra-actions need not involve humans. Also note that phenomena should not be understood in a phenomenological sense but as particular material entanglements.

14 According to Newtonian physics, the two variables that need to be specified simultaneously are position and momentum. According to Bohr, causality in the Newtonian sense of strict determinism cannot hold because mutually exclusive apparatuses are required to define "position" and "momentum."

15 See chapter 4 for more details of my diffractive reading of the insights of Bohr and Butler and Foucault through one another to provide a posthumanist performative understanding of material-discursive practices, including those called "technoscientific," those identified as "social," and those identified as "natural."

16 The extension of Bohr's analysis from the physical-conceptual to the material-discursive also depends on a fuller account of materiality than that offered by Foucault (see hereafter). It also requires a posthumanist understanding of discursive practices—see chapter 4. Foucault's analysis of the productive effects of power/knowledge systems on bodies is limited to human bodies (see note 28 hereafter) and "social" practices. See Rouse 1987 for a detailed philosophical analysis of the extension of Foucault's notion of power/knowledge to the domain of the natural sciences.

17 "What was new, in the eighteenth century, was that . . . the disciplines crossed a 'technological' threshold . . . [whereby hospitals, schools, and workplaces] became . . . apparatuses such that any mechanism of objectification could be used in them as an instrument of subjection, any growth of power could give rise in them to possible branches of knowledge; it was this link, proper to the technological systems, that made possible within the disciplinary element the formation of clinical medicine, psychiatry, child psychology, educational psychology, and the rationalization of labour" (Foucault 1977, 224).

18 See chapters 4, 6, and 8 for more details of my agential realist elaboration of the nature of contemporary forms of power.

19 Which is not to deny the complex nature of reading practices necessary for making sense of photographic images more generally but to emphasize the technical training required for reading ultrasound images.

20 Bohr is completely inattentive to the temporal nature of apparatuses and practices. Bohr's analysis starts with the possibilities for selection of instrumentation, for example, devices with movable parts or devices with fixed parts; he doesn't say anything about the practices that produce the instrumentation, and doesn't acknowledge that apparatuses are constantly reworked as part of the practices that produce phenomena. See chapter 4.

21 Because of the nature of intra-activity, phenomena that are in the process of materializing are always already implicated in other practices that are in the process of materializing other phenomena. This is not to say that intra-activity is a deterministic dynamics. On the contrary, as I have already alluded to and will discuss more thoroughly later in this chapter, intra-actions entail a reworking of the notion of causality. Intra-actions are constraining but not determining. Materialization is an open-ended (but nonarbitrary) process. See also chapter 4.

22 See Barad 2000b on doing responsible science and an agential realist reworking of the issue of (scientific) literacy. See chapter 8 for an agential realist reformulation of ethics.

23 Materialization is taken up in detail in the next section. The notion of materialization that is suggested here shares some important features with Butler's notion (e.g., materialization in both cases is a temporal and open process), yet it differs from (and goes beyond) Butler's account in other ways discussed hereafter. See also chapter 4 for an agential realist account of materiality, temporality, and performativity.

24 Piezoelectric materials are used for many nonmedical applications, as well. One company has used piezoelectric materials to develop "smart skis," skis that "know" how to damp different vibrations to maximize contact between the ski and the snow. "Smart technologies" were developed in conjunction with other aerospace and military applications of piezoelectrics that address vibration problems. Boeing, Rockwell, Lockheed Martin, Honeywell, McDonnell Douglas, Northrop Grumman, General Electric, Bobcox and Wilcox, Westinghouse, Racor, TRW, and Raytheon are some of the main customers.

25 In the current and recent political climate in the United States, the objectification of the fetus is related to its subjectivation as the patient and the "desubjectivation" of the pregnant woman as a "container" or "maternal environment" for the fetus. The feminist literature on this topic is vast. Casper 1998 and Hartouni 1997 are two important recent references.

26 For Bohr, or at least in my elaboration of Bohr, not only are what is produced and what is excluded co-constituted, but the "constitutive outside" is a matter of material-discursive exclusions (not simply discursive ones). That is, intelligibility and material conditions of exclusion are indissociable.

27 Neither is his notion of discursive practices. See my posthumanist elaboration of discursive practices and performativity in chapter 4.

28 Butler cites a particular passage in *Discipline and Punish* (Foucault 1977, 30) as evidence that Foucault theorizes the materialization of the prison as well as the prisoner (Butler 1993, 34). I think that at best this is an exceedingly generous reading of this passage. I read Foucault's point as insisting on the importance of the material arrangements that constitute the prison (and sustain particular discourses) and are the basis for its efficacy as an instrument of power. I do not take this to mean that the materiality of the prison is constituted through being taken up in power relations. In any case, Foucault clearly does *not* give a developed account of the materialization of nonhuman (including inanimate) bodies. In fact, the account of materialization that he does give depends on a "soul," in particular, the fact that "the soul is the prison of the body" (1977, 30). I do think that Butler's impulse (at least in this particular passage) to theorize the materialization of nonhuman bodies as part of a theory of the materialization of human bodies is absolutely correct, but she does not follow this impulse through in theorizing materialization in a way that accounts for the materialization of nonhuman bodies and practices of mattering through which the human and the nonhuman are differentially constituted. Indeed, what is ultimately needed is an account of materiality that seeks to understand the practices by which materiality is an agential force in the very drawing of the boundaries between the human and the nonhuman. I take up this question specifically hereafter and in chapter 4.

29 It is interesting to note the resonance between Bohr's and Butler's challenges to representationalism. In *Bodies That Matter*, Butler writes: "The body posited as prior to the sign, is always posited or signified as prior. This signification

produces as an effect of its own procedure the very body that it nevertheless and simultaneously claims to discover as that which precedes its own action. If the body signified as prior to signification is an effect of signification, then the mimetic or representational status of language, which claims that signs follow bodies as their necessary mirrors, is not mimetic at all. On the contrary, it is productive, constitutive, one might even argue performative, inasmuch as this signifying act delimits and contours the body that it then claims to find prior to any and all signification" (1993, 30).

30 See chapter 3.

31 The extension of Bohr's analysis from the physical-conceptual to the material-discursive requires a posthumanist understanding of discursive practices and material phenomena—see chapter 4.

32 Apparatuses may (but need not) include both humans and nonhumans. In any case, apparatuses are *not* to be understood as assemblages of preexisting, separately determinate individuals of one kind or another.

33 Phenomena are ontological primitives (i.e., they are relations without relata). In a sense, phenomena are the new atoms where atoms are not individual objects but rather practices/doings distributed in space and time. See chapters 4, 7, and 8.

34 See chapters 4 and 8 for a posthumanist (i.e., not human-based) conception of intelligibility. In short, intelligibility is a matter of determinateness (an ontological notion through which what matters—materially and semantically—is "spelled out"). It is not a human-based epistemological conception. See also the discussion of the agential realist reworking of traditional conceptions of ontology and epistemology.

35 What is at issue is not merely the addition of material and discursive constraints, but indeed their mutual implication.

36 The mutually informative methodology of diffractively reading texts (theories) through one another is a particularly apt form of analysis for agential realists. Reflection, by contrast, and other means of reading one text against another involve reification or the fixing of one text against which the other is viewed. In a related fashion, agential realism suggests the notion of *intra-action* as a nondeterministic alternative dynamics to the limiting notions of the *influence, impact, or embedding* of one factor on or in another. To assume a dynamics of influence is often to wrongly attribute agency to reified notions called Culture, Power, Discourse, et cetera. See chapter 2 for a more detailed discussion of a diffractive methodology.

37 Ironically, although one of Butler's primary concerns is the nature of abjection and the processes through which the human is differentially constituted, Butler's account of materialization privileges human bodies from the start.

38 More precisely, what is at issue here is the mutual implication of the material and the discursive, where discursive practices are to be understood according to my posthumanist (i.e., not human-based) formulation as specific material configurations or reconfigurings of the world. See chapter 4.

39 Advocates of empiricism and many of its challengers share in the presupposition of a Newtonian conception of matter: the point of contention between them is generally framed in terms of whether or not one takes the mediation of matter by language, the social, power, or other intermediaries to be benign or not; but the underlying ontology is generally not questioned. In contrast, according to agential realism, it is not necessary (or correct) to secure matter as a fixed substance with inherent properties to take into account how matter comes to matter.

40 Monica Casper has criticized actor network theory's account of material agency for its troubling implications concerning the status of the fetus as a subject. Recognition of material agency within the context of agential realism is not problematic in this sense both because the emergence and constitution of the subject are part of what is at issue and because agency is not aligned with subjectivity. For details see hereafter.

41 In point of fact, Butler contends that "the controversy over the meaning of *construction* appears to founder on the conventional philosophical polarity between free will and determinism" (1990, 8). She points out that the free will–determinism duality limits our thinking so that "the body" gets conceived of either as "a passive medium on which cultural meanings are inscribed or as the instrument through which an appropriative and interpretive will determines a cultural meaning for itself. In either case, the body is figured as mere *instrument* or *medium* for which a set of cultural meanings are only externally related. But 'the body' is itself a construction. . . . The question then emerges. . . . How do we reconceive the body no longer as a passive medium or instrument awaiting the enlivening capacity of a distinctly immaterial will?" (1990, 8).

42 Agency and its connection to issues of responsibility and accountability are central elements of agential realism. For further discussion, see chapter 8.

43 The science studies literature is replete with discussions of "material," "nonhuman," and "cyborgian" forms of agency. These include, for example, the actor-network theories of Callon, Latour, and Law, as well as other approaches by Haraway (1991), Pickering (1995), and Rouse (1996). The issue of agency is squawked about in the infamous "epistemological chicken" debates in science studies (see Pickering 1992). The central figures in the debates include Harry Collins, Steven Yearley, Steve Woolgar, Michel Callon, and Bruno Latour.

There is an unfortunate tendency in the science studies literature to conflate questions of "material agency" and "nonhuman agency." In particular, there is a tendency to conflate "material" with "natural" or "nonhuman," counterposing the "material" world with the "human" one (as if humans are not material?), sequestering what is human to the purely cultural domain (as if culture is not material?), which is an ironic reinscription of precisely what is being contested. So, for example, some science studies scholars use the term "material agency" to mean "acts of nature." By contrast, when I talk about "material agency" or "matter's agency," I do so to emphasize matter's dynamism against the more usual conception of matter as passive and inert, but not against "human agency." (Which, of course, is not to say that material agency is separate from discursive agency, since matter is always already material-discursive, and discursivity is not to be understood as a human-based practice.) See chapter 4. The point, in any case, is not to attribute agency to nonhumans as well as humans but to rethink the notion of agency, and to understand the agential practices through which the human and the nonhuman are differentially constituted.

44 The fact that pregnant women are referred to here as "apparatuses" should not be taken to mean that women are mere instruments or technologies for the development of the fetus. The notion of "apparatus" developed here differs significantly from more common uses of the term. As remarked earlier, material-discursive apparatuses are themselves phenomena made up of specific intra-actions of humans and nonhumans, where the differential constitution of human (or nonhuman) itself designates a particular phenomenon, and what gets defined as a subject (or object) and what gets defined as an apparatus are intra-actively constituted through specific practices.

45 See Caridad Souza's (1999) important ethnographic research on, and analysis of, the racialized nature of the public discourse on personal responsibility and its displacement of state accountability.

46 Progress has been made on this front since this article was published in 1998. In April 2004 a collaboration of Japanese and Korean academic and industry-based scientists published an article in the journal *Nature* announcing the successful production of a mouse through parthenogenesis: "We have shown for the first time that it is possible to obtain a viable adult mouse from two maternal genomes" (Kono et al.2004, 863). The parthenote was not only viable but grew to adulthood and produced its own offspring (i.e., it was found to be fertile). (Note: Gynogenesis differs from parthenogenesis in that stimulation [but not fertilization] by sperm is required to stimulate the egg to develop into an embryo. Parthenogenesis is the ability of unfertilized eggs to develop into embryos in the absence of sperm. Whiptail lizards [see the poem by Alice Fulton in Appendix A] are a parthenogenetic species.) The successful parthenogenesis was achieved by controlling the expression of two particular genes in the parthenogenetic embryos. "Imprinted genes are epigenetically marked during gametogenesis so that they are exclusively expressed from either the paternal or the maternal allele in offspring" (Kaneda et al. 2004, 900). The scientists who engineered the viable parthenote conclude: "These results suggest that paternal imprinting prevents parthenogenesis, ensuring that the paternal contribution is obligatory for the descendant" (Kono et al. 2004, 860).

See also the BBC article "Mice Created without Fathers" (April 21, 2004). Comparing the *Nature* article with the BBC report makes for a fascinating (course) exercise. For example, the BBC report states: "The phenomenon, called parthenogenesis, never occurs naturally in mammals." Compare with the *Nature* article: "Only mammals have relinquished parthenogenesis, a means of producing descendants solely from maternal germ cells." Or the BBC report: "The genetic manipulation carried out by the researchers gave the genes a more paternal character." The *Nature* article: "Nevertheless, this study emphasizes the fact that normal development in mice is subject to a rigorous 'conflict' and differences due to imprinting of maternal and paternal." It is interesting to note that the BBC article emphasizes the low efficiency of the technique and the impossibility of its application to humans.

47 While this can be seen as a disruption of the presumed equivalence of the biological and genetic mothers, Sarah Blaffer Hardy makes the important point that mothers raising nongenetically related children are properly biological mothers, since biology is much more than genetics (private communication).

48 Information about 3-D ultrasonography and a plethora of 3-D ultrasound images are available on the World Wide Web. For a history of the use of ultrasound in obstetrics and gynecology, see especially http://www.ob-ultrasound.net/history.html. So-called 4-D ultrasonography is also readily available now. The fourth dimension that is alluded to is the element of time (it's just a slick marketing name and has nothing to do with the physics of special relativity in its reference to time as the fourth dimension). 4-D ultrasound images are a succession of 3-D images, so-called real-time imaging. Websites advertising 4-D ultrasound promise to send the "parents" home with their "first home movie": a prebirth video.

49 The technical name for what I am calling a "virtual scalpel" is a "volume interactive electronic scalpel" (Nelson and Pretorius 1997).

50 The subjectivation of the fetus through ultrasound technology was discussed earlier. Additionally, three-dimensional ultrasonography has the potential to obscure the patient's subjectivity: "Acquisition of volume patient data also affords the possibility of review after the patient has left the medical facility or communication of the entire volume via an interactive communications link to a specialist at a tertiary care center. This could reduce the need to refer a patient to a specialized center by permitting the primary physician and the specialist to consult and interactively review the study from both sites thus improving patient care and reducing costs" (Nelson and Pretorius 1997). While this feature has some obvious benefits, it also has the potential to remove the patient from the decision-making circuit.

51 I would like to thank Laura Liu for some wonderful discussions concerning the great untapped potential of engaging in mutually informative conversations among feminist scientists, feminist science studies scholars, and feminist theorists, and for giving me this wonderfully succinct way of making this point here.

SIX • SPACETIME RE(CON)FIGURINGS

1 This vignette was written for the purposes of the arguments that follow. I return to the issues that it raises in the chapter's conclusion.

2 The point that I want to make is not solved by the move from Euclidean geometry (geometry of flat space) to non-Euclidean geometry (geometry of curved space). Whether space is imagined as flat or curved, the spatial metaphors that are deployed entail a geometrical imaginary that I am calling "Euclidean" in that they are associated with an image of space as a container within which things are placed and find themselves in geometrical relationship to one another (i.e., the question is not the shape *of* space per se so much as shapes *in* space).

I thank Laura Liu for bringing to my attention a paper by Neil Smith and Cindi Katz (1993) that similarly cautions against the uncritical embrace of spatial metaphors, particularly when many of the spatial metaphors that feminist and other theorists rely on are rooted in a modernist representation of space as absolute. Presenting a very interesting sketch of the history of its modernist conception, they argue that "this space is quite literally the space of capitalist patriarchy and racist imperialism" (79). Also, a faculty seminar at Smith College on postcolonial feminisms brought Caren Kaplan's "Postmodern Geographies" to my attention. In this chapter of her book *Questions of Travel*, Kaplan (1996) addresses similar issues but gives a different justification for the feminist reliance on spatial metaphors by tracing the history of its theoretical purchase within feminist discourses. Ultimately she argues that feminists should not abandon the notion of location but reconsider its meaning; she encourages us to think of location as "an axis rather than a place" and suggests that location be understood as a frame for investigating the production of different identities (183). This shift is intriguing, but the notion of location that Kaplan proposes reinscribes the Euclidean container model of space, rather than providing the needed understanding of spacetime as a dynamic and changing topology. I thank Caren for her gracious engagement with my critique and some other wonderful conversation during her visit.

3 See Adrienne Rich's "Notes toward a Politics of Location" (1986). More recent elaborations include Frankenberg and Mani 1993 and Kaplan 1994. It is interesting in thinking through this genealogy to read Haraway (1988) as an engagement with, and reworking of, Rich's "politics of location."

4 Of course, a crucial ingredient of critical political praxis is the ongoing contestation of those very norms, but this is not to deny their relevance to such practices.

5 Admittedly, the metaphor of a framework harkens back once again to the image of a Euclidean geometrical structure. It isn't surprising that the pervasiveness of the Euclidean imaginary haunts even its possible reimaginings. The point here is not to banish all such conceptualizations as a matter of principle but to think critically about the implicit reliance of contemporary theories on this taken-for-granted understanding of spatiality and the constraints it poses on theorizing. While "framework" may connote some of the weight and rigidity of structure, the notion of structure (in a poststructuralist sense) is in fact being reworked in this chapter.

6 At least this is true of earlier works of Hennessy, like Hennessy 1993.

7 On the methodology of diffractive reading, see chapter 2.

8 While poststructuralists largely eschew talk about structures as such, networks, rhizomes, and fluids are some of the forms that get taken up with considerable enthusiasm these days. Of course, the latter forms are not without structure, but clearly they differ in important respects from the kinds of hierarchical formations of external forces that structuralists focus their energies on. "Structures" in this chapter are not to be understood in a structuralist sense but in a more general poststructuralist sense. Indeed, I will argue that structural relations are specific material (re)configurings of bodies, that is, ongoing re(con)figurings of space-time-matterings.

9 Fernandes uses the term "community" to designate "a broad grouping that includes identities of religion, region, caste, and language" (11).

10 Of course, Fernandes is not alone here in her objections to these all-too-common conceptions, but her attention to specific practices of spatialization produces a uniquely visual account of how intersectionality operates through everyday practices. This may be one reason students find her account particularly helpful in understanding intersectionality, at least in my experience.

11 The neologism "intra-action" and the hyphenated structure "material-discursive" are explained in chapter 4. See also the discussion in chapter 4 on the question of the boundaries of an apparatus. Apparatuses are dynamically made and remade through different kinds of boundary-making practices. Indeed, the articulation of a given apparatus is always already a boundary-making practice. At the same time, not all apparatuses contribute equally to processes of materialization, and genealogical investigations of the most important apparatuses and the nature of their intra-actions are needed for thoroughgoing political analyses (see chapter 8 and Barad 2000b). "What constitutes an apparatus of bodily production cannot be known in advance of engaging in the always messy projects of description, narration, intervention, inhabiting, conversing, exchanging, and building. The point is to get at how worlds are made and unmade, in order to participate in the process, in order to foster some forms of life and not others" (Haraway 1994, 63).

12 Machines are one thing in Newton's universe, where the great clockwork keeps on ticking and humans are just one more cog in the machine, and quite another in the postquantum era, where humans and machines are more intimate than Newton could have imagined, and apparatuses are more lively than ever.

13 Of particular relevance for the discussion in this chapter are the limitations of Foucault's conception of space, time, and matter. David Harvey and Gayatri Spivak are among those who charge Foucault with holding onto a modernist conception of space. Harvey (1990) explicitly characterizes Foucault's conception of space as a "container of power," and Spivak notes that "Foucault is a brilliant thinker of power-in-spacing, but the awareness of the topographical reinscription of imperialism does not inform his presuppositions" (1988, 292). Haraway points out that Foucault holds onto a modernist conception of time as well (1997, 12). See my remarks on the limitations of Foucault's and Butler's accounts of matter and materialization in chapter 4. My elaboration reworks space, time, and matter in important ways that are explored below.

14 See Chapter 4 for more details of my diffractive approach reading the insights of Bohr and Butler and Foucault through one another to provide a posthumanist performative understanding of material-discursive practices, including those called "technoscientific," those identified as "social," and those identified as "natural."

15 The real is not constituted by a collapse of the existing set of possibilities; it is not a singular selection among present alternative possibilities (see chapter 7).

16 This sense of aliveness applies to the inanimate as well as the animate, or rather it is that which makes possible the very distinction between the animate and the inanimate.

17 The Foucauldian notion of power is not the historically dated notion of sov-

ereign power, which continues to function as the dominant cultural image, but rather, a set of immanent relations of force:

> By power, I do not mean "Power" as a group of institutions and mechanisms that ensure the subservience of the citizens of a given state. By power, I do not mean, either, a mode of subjugation which, in contrast to violence, has the form of the rule. Finally, I do not have in mind a general system of domination exerted by one group over another, a system whose effects, through successive derivations, pervade the entire social body. The analysis, made in terms of power, must not assume that the sovereignty of the state, the form of the law, or the over-all unity of a domination are given at the outset; rather, these are only the terminal forms power takes. It seems to me that power must be understood in the first instance as the multiplicity of force relations immanent in the sphere in which they operate and which constitute their own organization; as the process which, through ceaseless struggles and confrontations, transforms, strengthens, or reverses them; as the support which these force relations find in one another, thus forming a chain or a system, or on the contrary, the disjunctions and contradictions which isolate them from one another; and lastly, as the strategies in which they take effect, whose general design or institutional crystallization is embodied in the state apparatus, in the formulation of the law, in the various social hegemonies. (Foucault 1978, 92–93)

18 Fernandes does not merely track the position of workers on the grid of the shop floor as a Newtonian physicist tracks the successive positions of an object in space; rather, she traces the dynamic contested production of the spatiality of the shop floor.

19 Apparatuses are not individually separable or determinate, since they are always already implicated in ongoing intra-actions and enfoldings. Traditionally, however, they have been treated as separable: for example, some have been labeled "economic" and some (mis)identified as "merely cultural" (that is, having to do with the "politics of recognition," as opposed to the "politics of redistribution"). In *Justice Interruptus*, Nancy Fraser (1997) argues against making "an either/or choice between the politics of redistribution and the politics of recognition" (4), yet her starting point is to set up redistribution and recognition as perpendicular—that is, entirely separate—axes of a coordinate system of injustices (the metaphor is hers). This analytical boundary cut (drawing a line around the economic as singularly a matter of class, contra Fernandes), which Fraser herself readily admits is artificial, limits her attempt at synthesizing the very elements she insists on separating at the outset. As Judith Butler (1997) argues, Fraser's analysis reinscribes the problematic conception of social identities as merely cultural. (See also Fraser's response to Butler in the same volume.) Indeed, Fraser's conception of materiality is limited to the merely economic. This stands in contrast to the alternative conception of materiality offered here. I want to thank Nancy Fraser for an interesting interchange about this point during an IRW faculty seminar at Rutgers in the fall of 1997.

20 Miranda Joseph (1998) also argues for an expanded understanding of production that includes the productivity of performativity (where performativity is understood by Joseph in an expanded sense of its own as a form of production) in an effort to dislodge the taken-for-granted opposition between the economic and the social.

21 See Haraway 2003.

22 The use of the notion of "assemblage" is risky here, since assemblages are generally assumed to be collections of individual determinate objects. Importantly, apparatuses are *not* assemblages of preexisting, separately determinate individuals of one kind or another. It is crucial to remember that these "gears" are intra-acting "components," not preexisting ones.

23 Production processes involving nano, info, and bio-technologies are instances where the shifting of boundaries between human and nonhuman is perhaps most evident and most thoroughly analyzed, though they are not the only ones. The literature on this subject is extensive; see, for example, Haraway 1997; Gray 1995; and chapter 8.

24 My critique of their assumed separability (as individually determinate entities) should not be misunderstood as a suggestion that these categories ought to be collapsed.

25 Poststructuralist responses to Althusser's inadequate theorizing of the workings of power through a rigidified, separable, and determining conception of agential dimensions of power—a formulation that lacks the important recognition of the productive effects of power—has produced an aversion to terms like apparatuses and structures. I have retained these terms, suitably revised of course (to contest many of their structuralist features), that is, as a refined analytical tool, in an effort to help track and take account of the nature of entanglements and the complex dynamics of intra-activity. A full accounting of the workings of power requires a genealogy of the material-discursive apparatuses of bodily production and how they matter and for whom. Suitably refined tools are needed for these crucial tasks. I am suggesting that apparatuses may turn out to be tools worth keeping handy among other instruments in our toolboxes.

26 Geometry is concerned with shapes and sizes (this is true even of the non-Euclidean varieties, such as geometries built on curved surfaces like spheres rather than on flat planes), whereas topology investigates questions of connectivity and boundaries. Although spatiality is often thought of geometrically, particularly in terms of the characteristics of enclosures (like size and shape), this is only one way of thinking about space. Topological features of manifolds can be extremely important. For example, two points that seem far apart geometrically may, given a particular connectivity of the spatial manifold, actually be proximate to one another (as, for example, in the case of cosmological objects called "wormholes").

27 The literature on intersectionality is extensive. The Consortium on Race, Gender, and Ethnicity at the University of Maryland, directed by Bonnie Thornton Dill, has an online intersectionality research database (http://www.crge.umd.edu). The term "intersectionality" is commonly attributed to Crenshaw (1989).

28 This summary of the topological nature of this production doesn't do justice to

her analysis of spatiality and temporality as constitutive factors of this dynamics. To appreciate this crucial aspect, one needs to take in the details of her empirical account of the shifting patterns of relations, that is, the reworking of diffraction patterns or differential patterns of mattering.

29 Critical theory seems to be in love with "the new" these days. But how new is this love affair with the new? And what does it signal about contemporary material conditions? It certainly seems to be right at home with an economy of waste that endorses tossing out "the old" when it no longer seems to work, and immediately plugging in and going online to purchase "the new." The equation of the new with youth, originality, chaos, and revolutionary breaks with the past provides clues to the affective force field at work and the seductive pull of particular kinds of figurations. Which is also not to endorse the valorization of the old in the misguided equation of it with wisdom, indigenous knowledge practices, and a return to better times. Both forms of valorization are romantic affairs, and the shift in temporality that agential realism entails undermines the sense of past, future, and change that supports such categorizations.

30 For example, one might assume that a more complete genealogical analysis of the jute industry today would include the replacement of jute by new synthetic materials, interests of agribusiness, including agricultural "vulnerabilities" of the jute crops, proposed biotechnology fixes, such as genetic modifications to try to make the plants caterpillar and flood resistant, and the economics of trade as influenced by global trade agreements (such as the Agreement on Agriculture of the World Trade Organization), among many other factors. (The specifics of these agricultural and economic considerations postdate Fernandes's 1990–91 fieldwork, but the same point applies.) See chapter 4 on the question of where the apparatus ends. The unboundedness of the apparatus does not imply that everything and anything matter equally.

31 According to Marx, uneven development is intrinsic to capitalism. For contemporary analyses of uneven development, see, for example, Smith 1991; Massey 1984; Storper and Walker 1989.

32 This important work has already begun. See, for example, the groundbreaking work on corporate genealogies being done by Barbara Harlow, Punima Bose, Laura Lyons, and Rachel Gennings (panel at the Rethinking Marxism Conference, September 23, 2000).

33 Panel at the Rethinking Marxism Conference, "Rosa and Ruth/Terror and Truth—Dialogue," with Ruth Wilson Gilmore and Barbara Harlow, September 24, 2000.

SEVEN • QUANTUM ENTANGLEMENTS

1 All the references to pipes, cigars, and similar implements in this book—like Niels Bohr's companion pipe which accompanied him everywhere, Otto Stern's Nobel Prize–winning cigar, and René Magritte's not-a-pipe—signal disruptions, dislocations, and challenges to representationalism and the concordant view that we are distant observers, and not participants, in the world. That is, I draw on the metaphor of smoke in order to displace the illusion of mirrors, particularly representationalism's obsession with reflection and the view from a distance, because an epistemology premised on a pre-established separation between subject and object makes for an illusionary optics of knowing. Distance does not guarantee separation or even separability. Knowing is not a matter of reflecting at a distance; rather it is an active and specific practice of engagement. To know is to become entangled; objectivity requires that one take responsibility for one's entanglements. What is at issue then in securing objectivity, as we'll see later in this chapter, is not disentangling and disengaging, but agential separability and accountability (see also chapter 8).

2 Bohr's account of scientific practices is not naturalistic in the sense of giving science unquestioned authority to speak for the world, on the contrary; but he might well have embraced Rouse's (2002, 2004) suitably revised conception of naturalism that takes seriously what our best scientific theories tell us while simultaneously holding science accountable for its practices, for its own sake as it were, in order to safeguard objectivity and its naturalist commitments.

3 The first kind of equation is not tricky at all; two terms are multiplied together and then added, and all that represents is the addition—that is, superposition—of waveforms. Recall that when waves overlap the resulting amplitude is simply the sum of the amplitudes of the individual waves. The other kind of equation represents an entanglement, which we'll see, is simply a generalization of a superposition.

4 Some advice to the nonspecialist: If a particular idea isn't clear, give it a placeholder name like you would a character in a play or a novel that seems impossible to understand or has a name that seems impossible to pronounce, and carry this character along in its bracketed form while paying attention to the story line despite this uncomfortable piece. In other words, don't give up, see if you can get the main idea, or even a sense, or perhaps just a glimpse of what is at issue and skip the details at first. You can go back to the details once you have a larger picture. Also, although they build on one another, it is possible to skip entire sections and get a sense of some of the important issues and the profound beauty of this subject.

5 As relayed by Erwin Schrödinger (1958, 170); see Jammer 1974, 24.

6 A "wave function" is a mathematical device for keeping track of how the "particle's" associated "wave" varies in space and time. The question of the nature of the wave function is taken up later in the chapter.

7 Imaginatry numbers are multiples of the square root of -1, symbolized by i. The "complex numbers" are an extension of the real numbers. Complex numbers contain an "imaginary" part and can be represented in the form $a + bi$, where a and b are real numbers and $i^2 = -1$ or $i = \sqrt{-1}$.

8 See, for example, Bohm 1952 and Bohm and Hiley 1993 on the Bohmian interpretation of quantum mechanics where the wave function is understood to "guide" the particle's motion. That is, it takes both the notions of wave and particle as real entities.

9 The so-called Copenhagen interpretation includes Bohr's complementarity

principle, Heisenberg's uncertainty principle, Born's probability interpretation, and von Neumann's projection postulate, among others. The discussion hereafter highlights some of the inconsistencies among these elements. See also Beller 1999.

10 As Richard Feynman put it: "If you have a problem, the real test of everything—you can't leave [it] alone—you've got to get the numbers out; if you don't get down to earth with it, it really isn't much. . . . [The] perpetual attitude [is] to use the theory—to see how it really works is to really use it" (quoted in Schweber 1986, 466). According to Sam Schweber, a physicist and historian of physics, "The defense connection during the 1950s reinforced the pragmatic, utilitarian, instrumental style so characteristic of theoretical physics in the United States. . . . The pragmatic ideal of American physics that had been visible from early on now became not only the national norm but in fact hegemonic worldwide" (Schweber 1989, 673). See also Barad 1994 for more details on how questions of the meaning of quantum physics were quickly excluded from the set of primary concerns that defined the field for American physicists. See Barad 1995 and 2000b for an examination of the implications of this pragmatic computational culture on science teaching and science literacy.

11 My subsection title is borrowed from the subtitle used by Haroche, Brune, and Raimond (1991), "Manipulation of Optical Fields by Atomic Interferometry: Quantum Variations on a Theme by Young." See chapter 3 for a detailed discussion of Young's two-slit experiment and wave-particle duality.

12 The solution specifies the behavior of the wave function in space and time. You may wonder what it is that is "waving" and what medium it is waving in. But the wave function is not a function in real-number space but rather exists in the space of complex numbers. Thus students are told that it doesn't make sense to try to visualize the wave function as we would a water wave or even an electromagnetic wave. Instead they are encouraged to think of it as a computational or bookkeeping device that contains all the information allowed by the uncertainty principle. In this way, the wave function is treated as something that is not itself physical but contains physical information. For example, the square (magnitude) of the wave function gives the probability (density) for finding a particle at a particular location x at a given time t.

13 Not all particles have two spin eigenvalues—either "up" or "down." Examples of particles with two spin eigenvalues include the electron. This simple case serves the purpose at hand—allowing us to get a handle on the nature of superpositions.

14 The example considered in this section involves the Stern-Gerlach apparatus. Those who have read chapter 4 will remember this experiment as involving Otto Stern's cheap cigar as a crucial ingredient in the production of visible traces.

15 I'm going to stop carrying along the caveat "to within experimental error." However, the reader should keep in mind that the result could be 101 particles through the top and 99 through the bottom, for example, and this would still be consistent with a 50–50 result to within experimental error (which we can expect to be of the order of $\sqrt{N}$ for N measurements). That is, all actual measurements have associated statistical errors that would have to be taken into account.

16 I have borrowed these three experiments from Townsend's (1992) elegant quantum mechanics textbook.

17 This is the case for all spin-1/2 particles, the case considered here, and in fact for all particles with spin greater than zero.

18 This modified SG device was first introduced by Feynman (see Feynman 1964, vol. 3). See also Townsend 1992.

19 It does seem to suggest that what may be at issue is the wave nature of matter (i.e., that the recombined beams interfere with one another). But there is also something remarkable about the fact that one can return as it were to the predisturbed state. This doesn't seem to work with Heisenberg's interpretation. See also the quantum eraser experiment (discussed later in the chapter).

20 When you think about it, there are plenty of quantities for which, given some particular circumstances, there is no fact of the matter. For example, while a particular mineral sample may have a determinate value of hardness on the Mohs scale, if we heat the mineral to very high temperatures, it will transform from a solid into a liquid or gas. When this happens there will no longer be any fact of the matter about the sample's mineral hardness value. Or consider a substance like water vapor. It doesn't make sense to apply the notion of mineral hardness to water vapor, and it doesn't have a determinate value of hardness. Likewise there is no fact of the matter concerning the temperature of a single particle or the color of something smaller than the wavelength of visual light.

21 See the discussion of Schrödinger's thoughts on this very point later in the chapter.

22 It is also possible to use the notion of a mixture in a quantum setting and talk of a "mixed quantum state" (which is a statistical mixture of pure quantum states). This is done in quantum statistical mechanics where both statistical and quantum descriptions are required (as provided by the density matrix), that is, where questions of both classical uncertainty and quantum indeterminacy arise.

23 The fact that there are situations that result in patterns intermediate between "wave" and "particle" does not contradict wave-particle complementarity (see the discussion later in this chapter of the work of Wootters and Zurek).

24 The distribution of particles on the screen is the probability density: particles are most likely to hit the screen where the intensity of the interference pattern is greatest. According to quantum theory, the probability distribution can be calculated from the wave function ψ. Specifically, the probability density is given by the square modulus of the wave function ψ (not just its square, since in general the wave function can be a complex number). Mathematically speaking, it is straightforward to see the difference between a mixture and an interference pattern. For a mixture, the pattern would be the result of the individual slit patterns: $|\psi|^2 = |a|^2\,|\psi_u|^2 + |b|^2\,|\psi_d|^2$, that is, a (overlapping) scatter pattern. By contrast, for a superposition the patterns is not merely the result of the individual slit patterns but also includes the interference or cross-terms: $|\psi|^2 = |a|^2\,|\psi_u|^2 + |b|^2\,|\psi_d|^2 + (a)^{*}b\,(\psi_u)^{*}\psi_d + a(b)^{*}\psi_u(\psi_d)^{*}$.

25 Not all superpositions manifest themselves as interference patterns, but all interference patterns are marks of superpositions. Mixtures do not produce interference patterns.

26 Einstein and his colleagues don't use the term "entanglement," which is introduced by Schrödinger in his 1935 paper motivated by the EPR paper. Nonetheless, as Schrödinger (1935) points out, the notion of entanglement is precisely at issue in the EPR paper.

27 This claim contains metaphysical assumptions such as locality and separability that are challenged by Bohr and by current experimental findings (see hereafter).

28 Just like superpositions, the possibility of entanglements is a direct consequence of the linearity of the SE.

29 Actually, this is not the example that Einstein and his colleagues used; in fact, it is the example David Bohm (1951) uses in his reconstruction of the EPR argument. Bohm's reconstruction in terms of the entanglement of two two-state systems is much more straightforward and mathematically less complex than the original EPR example. Also, in Bohm's example, the anticorrelation (correlation of the spins in opposite directions) is ensured by the conservation of spin angular momentum. Bohm's reconstruction was the basis for Bell's profound reworking of the EPR thought experiment into a real experiment that tests some of our deepest metaphysical assumptions. See Mermin 1985 for a beautiful exposition of the EPR experiment that is accessible to the layperson. I draw on Mermin's exposition in what follows.

30 Tests along just these lines were performed a half century after the publication of the EPR paper (see the following discussion of tests of Bell's inequality).

31 There is a mistake in the reprinting of Bohr's reply to Einstein, Podolsky, and Rosen in Wheeler and Zurek—pages 148 and 149 are mistakenly interchanged. A correct version is reprinted in *The Philosophical Writings of Niels Bohr*, vol. 4.

32 Most analyses of Bohr's response mistakenly take this point in the former, simplified sense.

33 I am interested here in the historical question of whether or not Bohr's response to Einstein and his colleagues was satisfying in the eyes of the physics community. The philosophical question of whether or not this little-appreciated point concerning the crux of Bohr's argument provides a satisfactory answer will be considered later in this chapter.

34 Besides, there was the 1932 proof of von Neumann that showed that it was not possible to construct a hidden variables theory that accounted for the results of quantum mechanics. This proof was later shown to contain a faulty assumption (Bell 1966). And also Bohm in 1952 constructed a working hidden variables theory, although the theory is explicitly nonlocal.

35 No doubt the intimate involvement of physicists in the war effort also contributed to their placing little value on resolving the foundational issues.

36 There is only one other very brief mention of the unfortunate feline in the entire paper, an injunction to "remember that poisoned cat!"

37 *Determinism* should not be confused with *determinateness*. The deterministic time evolution of the wave function as specified by the SE means that given the initial conditions, that is, the wave function at some initial time and appropriate boundary conditions, the wave function at all future times is determined. However, this determinism is not the strict determinism of classical physics, because the wave function itself is marked by an indeterminacy; that is, the notion of probability and of the possibility of getting different values upon measurement is inherent in the wave function itself (not in its evolution). So, as mentioned previously, whereas probability is an auxiliary notion in classical mechanics summarizing our ignorance or lack of complete knowledge, this is not its nature or its source in quantum theory. Therefore, indeterminism follows from quantum indeterminacy but the latter does not follow from the former. They are not equivalent, although many people mistakenly conflate these different notions.

38 Frequently, incorrect accounts of the paradox offer the simultaneously dead and alive interpretation and invite us to be shocked (and possibly horrified) by such an outcome, which is alleged to exemplify the bizarre nature of quantum phenomena. There is often a hint of the author taking great pleasure in the counterintuitive nature of a cat being both alive and dead, but this interpretation is not simply counterintuitive; it's wrong. Such an incorrect account not only misconstrues the state that the cat is in while in the chamber; it completely misses the crux of the paradox.

39 Assuming we pick appropriately normalized eigenstates for each subsystem.

40 As one system becomes entangled with another, through a mutual intra-action, the ontological indeterminacy in the form of a superposition of one of the systems before it intra-acts with another is spread over the system as a whole.

41 The related objection that Bohr's epistemological lesson applies only to the microscopic domain is also unfounded. First of all, as I will explain in the discussion that follows, quantum physics itself is *not* limited to the microscopic domain. Second, if quantum physics were limited to the microscopic domain (which it appears not to be), this would not necessarily (in and of itself) limit the general applicability of Bohr's epistemological and ontological insights which do not ultimately depend on quantum mechanics per se but rather are based on the existence of a fundamental discontinuity.

42 According to Bohr, this is precisely the reason why we were fooled for so long into thinking that we live in a classical world and that the classical epistemological and ontological assumptions apply. He noted that if Planck's constant had been larger, these false assumptions would have been ruled out much more readily or might not have ever occurred to us.

43 Recall from the foregoing discussion that a mixture is a state where each component system is in a determinate eigenstate.

44 That is, what is entangled is our knowledge of different systems.

45 For example, Beller (1999) denies that there is any relationship. I take issue with this view (see hereafter).

46 "The collapse of the wave function is a striking phenomenon, and the arguments we have given above make clear that it *must* occur" (Greenstein and Zajonc 1997, 185; italics mine). I point to this slip in the text by Greenstein and Zajonc not because the authors are themselves confused by the issues (see the

next quote, also taken from Greenstein and Zajonc, where there is a clear indication that they appreciate this point), or because the account plays fast and loose with what needs to be rigorously considered (not so), but on the contrary because this book is a truly excellent account of the foundational issues in quantum mechanics and therefore indicates just how strong this prejudice is. The book by Greenstein and Zajonc is an excellent text on quantum mechanics, which is unusual in its grounding in contemporary experiments.

47 At least I haven't seen any evidence of it. Bohr does mention the proof of von Neumann against the existence of hidden variables (which was later shown to be faulty) but does not mention his projection postulate.

48 In an effort to give a physical account of the collapse, physicists have proposed alternatives to the SE. See, for example, Ghirardi et al. 1986.

49 For an in-depth account, see Greenstein and Zajonc 1997, 190–93.

50 See my discussion earlier in the chapter.

51 The many-worlds interpretation is an extension by DeWitt and Graham (1973), and others of Everett's "relative state formulation." Its variations include many minds (Albert and Loewer 1988) and many histories (Gell-Mann and Hartle 1990). The many-histories interpretation is a version of the coherent-histories interpretation (Griffiths and Omnes 1999).

52 Originally published in the *American Journal of Physics* 47, no. 8 (August 1979): 718–21. Reprinted in *Reflections on Gender and Science* (Fox 1985).

53 Greenstein and Zajonc 1997 is an excellent resource on contemporary experiments on the foundational issues in quantum theory. Some of the experiments touched on here are discussed there in greater depth.

54 Quoted in Pais 1979.

55 Townsend (1992) uses "Al" and "Bert"—get it? Talk about your entangled states!

56 For a really beautiful conceptual discussion of Bell's inequality, see Mermin 1985. See Townsend for a clear mathematical treatment using elementary quantum mechanics.

57 The question of the "hidden" nature is irrelevant. And the issues are more properly described as locality and inherent determinateness (see discussion hereafter).

58 Sources on important theoretical clarifications include Kochen and Specker 1967; Jarrett 1984; Shimony 1986; Mermin 1990a, 1990b, 1990c, 1993; Redhead 1983; Wessels 1985; and Fine 1982. Early experimental tests include Freedman and Clauser 1972; Lamehi-Rachti and Mittig 1976; and Kasday et al. 1975. The most convincing experiments were conducted by Aspect et al. (1981, 1982a, 1982b). For an accessible review of the experimental tests, see Greenstein and Zajonc 1997.

59 For a refinement of these issues, see the discussion on separability hereafter.

60 See also Mermin 1993.

61 It should be noted that nonlocal contextual hidden variables theories are permitted by the BKS theorem. One such theory is the hidden variables theory of David Bohm (1952). Importantly, however, the nonlocal feature of his theory is not compatible with the special theory of relativity (i.e., Bohm's theory is not covariant). Note that there is an important difference between Bohrian "holism" and Bohmian holism. Bohm's theory involves a radical holism; everything matters (owing to the radical nonlocality), like traditional holism. By contrast, for Bohr, if one wants to apply the term "holism" at all (Teller), it must be understood that holism is about (specific) differences (and specific connectivities) that matter—differences within oneness, rather than oneness as a seamless, all-encompassing whole.

62 "Contextual" is not a particularly apt term. The notion of context connotes separability as a starting point: it presumes there is an object that exists apart from its environment or surroundings and that this environmental context matters in some way.

63 This account is from Heisenberg. The quote appears in Pais 1991, 302.

64 Heisenberg explained the source of the tension thus: "The difficulties in the discussion between Bohr and myself was that I wanted to start entirely from the mathematical scheme of quantum mechanics [by which Heisenberg means his matrix mechanics, not Schrödinger's wave mechanics] and use Schrödinger's theory perhaps as a tool sometimes. . . . Bohr, however, wanted to take the interpretation in some way very serious and play with both schemes" (quoted in Pais 1991, 303).

65 In this section, I refrain from calling this set of relations the "uncertainty relations," as is traditional, because for Bohr uncertainty is not the issue: there's no preexisting determinate property to be uncertain about. Instead I use the neutral term "relations of reciprocity."

66 These days this is referred to as interference–which-path complementarity rather than wave-particle complementarity. Some authors have made an issue of distinguishing the two, but this misses the very point that Bohr is making here: that the notions of "wave" and "particle" cannot be taken for granted but rather are meaningful only given appropriate experimental circumstances. In the two-slit experiment, the display of an interference pattern is what is meant by "wave" behavior.

67 I have taken the liberty of changing the symbols used to be consistent with modern-day conventions.

68 The correct interpretation of this passage depends on an appreciation of two other key features of Bohr's framework: his insistence on the necessary reliance on classical concepts, and the related notion of objectivity (see chapter 3). That is, Bohr argues that in making sense of quantum phenomena, we must rely on classical concepts, despite their inherent ambiguity; the crucial resolution of this ambiguity is provided by the larger experimental arrangement or "context." This ambiguity must be resolved to offer an objective description of phenomena. By "ordinary mode of description," Bohr means "classical description" (which refers to measured results, not to an injunction to use the laws of Newtonian physics.)

69 Bohr writes this equation as $\Delta x \, \Delta\sigma x \geq 1$ (Bohr 1963a [1925 essay], 59). The equations are identical if the relationship between k and σ_x is $k = \sigma_x/2$. I retain the original labeling of the equations as relations (1) and (2) (hereafter), following Bohr.

70 See also Barad 1995.

71 Notice that Bohr's derivation does not rely on the specificity of individual examples, like the two-slit experiment, despite the fact that it is sometimes claimed that the idea for individual complementarities comes from the examination of individual examples only. The basis of Bohr's derivation is wave-particle duality ($p \lambda = h$), and the principle of superposition (which is the basis for the derivation of equation [2a], which is a relationship that is true for all waves). Of course, the relative *degree* of definability of "position" and "momentum" depends on the specific experimental arrangement for each particular case.

72 This is Bohr's way of making the point about "contextuality" (previous section).

73 This is no small admission. That the addition of such a postscript was permitted rather than the admission of this error resulting in the rejection or withdrawal of the paper (or at the least an appropriate and thoroughgoing revision) opens up the interesting question about peer review and publishing practices at that particular historical juncture.

74 To make matters worse, some physicists have insisted that Bohr's principle of complementarity relies on the uncertainty principle as its mechanism of enforcement. See appendix B.

75 Bohr speaks of "which-course" rather than "which-slit" or "which-path" information. The terms have identical meanings. "Which-path" has become the standard term in these discussions. (Occasionally one also encounters the term "which-way" or the German *welcher Weg*.)

76 For further clarifications and insights on this issue, see Bartell 1980; Greenberger and Yasin 1988; Jaeger, Shimony, and Vaidman 1995; Englert 1996; Mandel 1991; Jaeger, Horne, and Shimony 1993.

77 In a refinement of the work of Wootters and Zurek, Greenberger and Yasin (1988) offer quantitative definitions of "wave" (ibid., equation [1]) and "particle" (ibid., equation [7]).

78 Wootters and Zurek go out of their way to explain that there is no contradiction between their findings and Bohr's principle of complementarity, and yet this crucial point has been lost on some authors who cite the findings of Wootters and Zurek to argue against wave-particle complementarity (Holladay 1998 is a case in point).

79 This is not to minimize the elegant analysis of Wootters and Zurek, who derive a quantitative relationship *specifically* for the modified two-slit experiment and find, as will be discussed, a rather surprising and important result.

80 For example, see Dürr, Nonn, and Rempe 1998; Summhammer, Rauch, and Tuppinger 1987.

81 See also the research on quantum beats. "We [Hellmuth et al.] need not actually perform a measurement that gives path information. It is sufficient that such an experiment is possible" (quoted in Greenstein and Zajonc 1997, 98).

82 These findings should relieve any lingering concern that Bohr's reply misses the main point of the EPR argument—which, as its authors argue, does not entail any direct measurement of the second system—a concern articulated by Faye and Folse in the following way:

> However, EPR's reasoning does not refer to the phenomenon *which actually occurs*, as Bohr demands, but rather to the outcome of *a possible observation*, which, if it were made on the second system, could be predicted with certainty on the basis of information obtained from an observation on the first system, and on the assumption that the experimenter has a "free choice" as to which possible observational phenomenon is actually realized. (Faye and Folse 1998, 4; italics mine)

It should be clear at this point that this objection is unfounded. Bohr is not talking about what happens when one *actually* performs measurements on system B (which the authors say they don't have to do); rather, he is talking about what is the case on the basis of *the conditions necessary* to perform measurements on system A and what the implications are for any *possible*, not necessarily actual, measurement then on system B (i.e., the premise of the statement by Faye and Folse is false).

83 See chapters 3 and 4.

84 More precisely, Scully et al. assert that "the actual mechanisms that enforce complementarity vary from one experimental situation to another" (1991, 111). Specifically, they accept that in the case of the recoiling-slit experiment, the uncertainty relations, governing the limitations on our knowledge due to a disturbance, are indeed the source of complementarity, whereas some other mechanism is required to explain how complementarity is enforced for the experiment that they propose.

85 From the perspective that I have presented here, Scully et al. seem to be reinventing the wheel: they show that which-path information can be obtained without there being any disturbance to the system under investigation, and they argue that the source of complementarity is the entanglement of the "measuring apparatus and the systems being observed." Understood against the background state of confusion about foundational issues in quantum physics, however, their account can be appreciated for the important contributions it makes in trying to sort out this complex set of issues.

86 Scully et al. (1991) point out that by their methods it is possible to realize Einstein's goal of circumventing the uncertainty principle, though not the goal of defeating complementarity: "Einstein's goal is indeed obtainable: it is possible to obtain *welcher Weg* [which-path] information without exposing the interfering beams to uncontrollable scattering events" (112). However, this is as far as things go; as Scully et al. show, it is, as Bohr says, not possible to obtain which-path information without destroying the interference pattern.

87 The work of Scully et al. spawned a discussion in the literature about the relationship between complementarity and the uncertainty principle. See appendix C for a summary of the controversy surrounding the question of the mechanism of enforcement of complementarity.

88 Including experiments by the Rochester group (including works by Zou, Ou, Wang, and Mendel), Eichmann et al. 1993; Chapman et al. 1995; Dürr et al. 1998; Herzog et al. 1995; Bjork and Karlsson 1998.

89 The idea of quantum erasers was introduced in Jaynes 1980; Scully and Drühl 1982; and Zajonc 1983.

90 Quantum eraser experiments have been performed by a number of different experimental groups on different physical systems. These include experiments reported in Ou et al. 1990; Zajonc et al. 1991; Wang et al. 1991; Kwiat et al. 1992; and Herzog et al. 1995.

91 The rather surprising idea of delayed-choice experiments is due to Wheeler 1978. Bohr warns that "causality" is yet another classical notion that needs to be rethought in light of the findings of quantum physics.

92 See the paper by Scully et al. (1991) for details of why the photon is registered by the detecting wall only half the time.

93 See also Howard 1985.

94 Other realist readings of Bohr have been offered in Folse 1985; Honner 1987; McKinnon 1994; and Favrholdt 1994.

95 See also Fine's 1986 essay "The Natural Ontological Attitude."

96 Don Howard (1985, 1989, 1997) makes a compelling argument that the question of separability is the main point of contention between Bohr and Einstein. While respecting the subtlety of Bohr's views, Howard's careful textual and philosophical analysis provides important insights into Einstein's commitment to separability, thereby providing much-needed clarity concerning the source of contention between them.

97 On "passion-at-a-distance," see Shimony 1984.

98 The term Jarrett used was "completeness," but Shimony (1986) suggested "outcome independence" instead for its greater clarity.

99 It is important to distinguish *locality* from *separability*. The locality principle "asserts that the state of a system is unaffected by events in regions of the universe so removed from the given system that no signal could connect them" (Howard 1989, 226–27). "Locality assumes for its formulation the existence of separate states, but they need not be of the kind assumed by the separability principle; that is to say, they need not be such as to determine completely the joint state of every composite system to which the systems they characterize may belong as parts. Thus, it is possible to have a *local*, but *nonseparable* theory, quantum mechanics being the most important example" (227).

100 That is, as far as Bohr is concerned, the question of correlations raised by Einstein and his colleagues is the same kind of question as the ones at issue in the examination of measurement processes, which Bohr had already addressed. "One of Bohr's points [in his reply to Einstein, Podolsky, and Rosen] is that there is nothing new or unusual about EPR correlations: Precisely the same kinds of correlations are set up in the measurement process, and therefore there is no cause for alarm because he has already straightened out that problem" (Mermin 1998, 767).

101 Einstein's theoretical masterpiece, the general theory of relativity, is a field theory of gravity. As Howard points out, fields are the instantiation of the principle of separability down to the level of individual infinitesimal points; that is, fields carry out the separability principle to the extreme. Ironically, current theories of quantum gravity propose a discrete, instead of continuous, field theory (see Smolin 2001 on loop quantum gravity).

102 One may object that this is a direct result of the fact that the laws themselves are symmetrical, but this observation just takes the same issue one step back.

103 I suspect that this principled ontological democracy may be at the root of some physicists' discomfort with feminist science studies as well, though if this is the case, much of this uneasiness has to do with a lack of understanding of what feminist science studies is. The suspicion that feminist science studies demands "special rights" for women, or feminine values, or feminist principles is unfounded. For one thing, this mistaken belief is premised on essentialist conceptions of gender and feminism that have been challenged *within* feminist theory. Feminist science studies scholars in particular staunchly oppose epistemological relativism, with an intensity shared by scientists (a fact that may come as a surprise to scientists and others who have not studied the feminist literature). This fact isn't at all surprising to those who realize that a substantial number of feminist science studies scholars, including some of the most highly regarded in the field, are scientists or at least have significant training in the sciences.

104 For a discussion of posthumanism, see chapter 4. Some philosophers may see the move I am making here as naturalistic. I have labeled this approach "posthumanist" rather than "naturalist" because the considerations that go by the former term are also interested in troubling the nature-culture distinction (though it is important to recognize that there are many different "posthumanisms; see the discussion in chapter 4), whereas naturalism (which also designates multiple stances) generally holds the nature-culture dualism in place. Rather than presuming an inherent distinction between nature and culture, I am interested in accounting for how this distinction is made and remade. However, see Rouse (2002, 2004) for a suitably redefined conception of naturalism.

105 The "main point" to which Bohr refers is, of course, the agential cut between object and agencies of observation.

106 Similarly, but not equivalently, Howard (1994) takes issue with the alleged coincidence of the classical-quantum and instrument-object distinctions.

107 Howard (1994) offers one of the finest analyses of this crucial point that I have seen. However, I find his presentation of what seems to be the same point rather confusing. Howard frames the issue by claiming that "Bohr required a classical description of *some*, but not necessarily *all*, features of the instrument" (203). This particular framing of this issue leads him to deny the coincidence of the object-instrument and quantum-classical distinctions. Instead I would argue that this correspondence does indeed hold (I think Bohr makes this point quite explicitly in the next quote I offer [1998 (1935 essay), 81]), and what needs to be clearly denied is the correspondence to a micro-macro distinction. However, I do not subscribe to what Howard calls the "coincidence interpretation" as it is generally held (since I deny its correspondence to a micro-macro distinction and insist on the variable-dependence of the role played, "object" or "instrument," by each part of the phenomenon). In my account, the central issue is the agential cut. There are fine distinctions. Overall, Howard and I share an interest

in sorting through Bohr's use of the term "classical" and the role it plays in his interpretation, and there are many similarities in our accounts.

108 The commitment to objectivity is a value shared by many, which is not to say that there is a consensus on what is meant by "objectivity." See Daston 1999 for a history of the notion of objectivity. Lloyd 1996 provides a useful philosophical taxonomy of the multiplicity of its meanings.

109 Bohr does mention that there is a "free choice on the part of the observer" concerning where this distinction is made (although for Bohr it must be made such that the instrument is macroscopic), but this is only insofar as he takes the observer to have a free choice about the selection of the experimental arrangement. That this is the only element of choice is made evident in the following quote by Bohr: "My main purpose in repeating these simple, and in substance well-known considerations, is to emphasize that in the phenomena concerned we are not dealing with an incomplete description characterized by the arbitrary picking out of different elements of physical reality at the cost of sacrificing other such elements, but with a rational discrimination between essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location or for a legitimate application of the conservation theorem of momentum. Any remaining appearance of arbitrariness concerns merely our freedom of handling the remaining instruments characteristic of the very idea of experiment" (1998 [1935 essay], 78). The question is whether this humanist assumption will stand as we continue our interrogation of the anthropocentric elements of Bohr's account. See chapter 4 and the discussion of a posthumanist elaboration of Bohr's account later in this chapter.

110 In *How Scientific Practices Matter* (2002), the philosopher Joseph Rouse examines a fundamental ambiguity in philosophical naturalists' claims to continuity between philosophy and the sciences and proposes a coherent naturalism that reconciles disparate commitments. Rouse disambiguates two strains of philosophical naturalism—one metaphilosophical (such that our preferred conception of scientific practices is understood as a natural engagement with the world) and one metaphysical (our preferred conception of nature is indeed what scientific inquiry discloses). His constructive project to develop a coherent philosophical naturalism, one that makes it possible to satisfy both strains of naturalism at once, thereby aims to "account for scientific *understanding* of nature as part of the *nature* to be understood" (i.e., this is one way to join these commitments into a coherent whole). Rouse draws on Bohr's philosophy-physics and agential realism in developing a coherent naturalism. See also Rouse 2004 for a naturalist reading of agential realism.

111 To even begin to comment on all the different interpretations of quantum mechanics in a way that does justice to each of them would require its own book. I do not begrudge anyone a favorite interpretation, and the fact that I have not commented on a particular interpretation should not been taken as a sign of dismissal. For my purposes here, I limit my comments to the interpretations that have interesting commonalities with my proposed relational interpretation.

112 I want to thank the physicist Amy Bug for encouraging me to think about the similarities and differences between Relational Quantum Mechanics and my agential realist interpretation.

113 Teller gives a more technical definition of particularism in terms of supervenience. For the particulars, see Teller 1989, 213.

114 In particular, not all phenomena have human components, that is, entail "human" agencies. See the discussion hereafter.

115 That is, relations are not secondarily derived from independently existing relata; rather, the mutual ontological dependence of relata—the relation—is the ontological primitive. As discussed hereafter, relata only exist *within* phenomena as a result of specific intra-actions (i.e., there are no independent relata, only relata-within-relations).

116 In my agential realist account, meaning making is not a human-based practice, but rather a result of specific material reconfigurings of the world (see chapter 4). Likewise, apparatuses are not merely laboratory instruments. Readers of this section are strongly advised to read chapters 3 and 4 before proceeding. These elaborations are crucial to understanding the agential realist interpretation proposed here.

117 Rouse (2002) also suggests that *measurement* need not be a term about laboratory operations, that before answering whether or not something is a measurement a prior question must be considered, namely, what constitutes a measurement of what?

118 Derivatively, the measured values can be unambiguously and contingently attributed to the corresponding property of "objects-in-the-phenomenon" (not to some presumably independent object). This is possible in part because we are in essence matching the separability implicit in classical concepts between "subject" and "object" to the agential separability between "object-in-the-phenomenon" and "instrument-in-the-phenomenon" (see Barad 1996). The contingent part of this relation must be attended to (i.e., it must be acknowledged that the objective referent is ultimately the phenomenon), or objectivity will be unachievable. See also Rouse 2002, chapters 8 and 9, on the derivative (not primary) attribution of measured values to objects-in-phenomena.

119 The "measurement problem" is understood by most physicists to be a dilemma concerning measurement in the colloquial sense of laboratory operations, not in the more general sense discussed earlier.

120 For example, as Scully et al. (1991) demonstrate via equation (7) of their paper, the fringes (i.e., cross-terms) vanish in the which-slit measurement because the system is entangled with the which-slit detector and the two different which-slit states are orthogonal. See also the analysis leading to equation (15) in the same paper.

121 Note that mixtures thus have an ontic meaning in terms of a contingent ontological determinacy, rather than the epistemic meaning in terms of uncertainty that we attribute to it classically. If, classically speaking, mixtures are a combination of individuals with determinate properties, quantum mechanically speaking, "mixtures" are to be understood not as a collection of individ-

ual entities with separately determinate boundaries and properties, but as agentially separable intra-acting states within a phenomenon.

122 Howard (1994) also makes these associations concerning the meaning of classical and quantum mechanical descriptions in a discussion concerning the nature of classical concepts (though not with regard to the measurement problem). My reading of Bohr's insistence on the necessity of classical concepts has greater affinity with Howard's reading than another that I know of, though there are some important differences (especially with regard to the important role of the agential cut and the question of the objective referent).

123 Ultimately, Peres offers an ensemble or statistical interpretation that does not necessarily follow. Instead it is possible to offer an ontological interpretation of pure and mixed states as suggested here (and in Mermin 1998).

124 Rovelli and Smolin make a similar point concerning their relational account. See hereafter.

125 Howard (1989) offers an explanation for the inconsistency of quantum mechanics and general relativity rooted in the question of (absolute) separability. This explanation may on the surface seem quite different from the difficulty that Smolin points to, but I would suggest that they are intimately related (i.e., that at root Smolin's point also goes to the issue of separability as we have seen earlier). In fact, as Smolin details, one of the current ideas is an approach that considers spacetime to be discrete rather than continuous; and, as Howard points out, fields are the instantiation of the principle of separability down to the level of individual infinitesimal points, that is, fields carry out the separability principle to the extreme.

126 The coherent-histories interpretation (Griffiths, Omnes, Hartle, and Gell-Mann) is sometimes offered as an elaboration of Bohr's insights in a way that allows for cosmological considerations.

127 See also Mermin 1998; Rovelli 1996; Teller 1989. Note that there are important differences among all these relational accounts.

EIGHT • ONTOLOGY, INTRA-ACTIVITY, ETHICS

My apologies to Alice Fulton for placing passages of her magnificent poem "Cascade Experiment" at what seems to be a considerable distance from one another. At least I have done so in good faith; for even a cut that breaks things apart does not cause a separation but furthers the entanglement! My hope is that the reader will understand these seemingly separate passages not as bookends framing the beginning and end of the book, or mere echoes of each other, but rather as an entangled state that reworks notions of contiguity and identity much as a poem does not so much touch our lives here and there, offering us individual moments of reflection, but rather gets inside our skin and reworks who we are. (For the full text of "Cascade Experiment," turn to appendix A immediately following this chapter.)

1 With a wink to Martin Buber.

2 All quotes (with permission) from the National Public Radio transcript, "Pushing Miniaturization Frontiers." The interview with Don Eigler, broadcast on July 17, 1996, was the third part of a *Morning Edition* series on nanotechnology.

3 See chapter 1 and the discussion in this chapter for more details on the workings of a scanning tunneling microscope. There is a wealth of resources on the STM and other new-generation microscopes, including some informative resources on the Web.

4 Moving the tip fractions of an angstrom (10^{-8} meter) at a time is not trivial. The mechanical technology doesn't exist. However, piezoelectric crystals have just what it takes (small changes with small currents), and are therefore used for the navigation of the tip in STMs.

5 The tunneling current (the flow of electrons between the tip and the sample surface) provides a measure of the distance between tip and sample surface. The metal tip never physically touches the sample surface; rather, the electrons tunnel from the tip to the surface. Tunneling is a purely quantum phenomenon without a classical analogue.

6 Richard Feynman's 1959 speech "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" to the American Physical Society is often credited as the origin of the nanotechnology revolution (see Feynman 1960).

7 The URL for the IBM STM image gallery is http://www.almaden.ibm.com/vis/stm/gallery.html. I highly recommend the "Atomic Fly-By" (http://www.almaden.ibm.com/vis/stm/stm.html).

8 The miniaturization of computer chips and magnetic disk drives is one goal of the race for nanotechnologies. The size of computer chips has been decreasing exponentially, and if the advance continues on this curve, chips are projected to reach the level of individual atoms by 2020. In fact, we already regularly depend on technologies at this scale. For example, the bumps that encode binary information on the surface of a compact disc are only hundreds of nanometers in size. Hard disks inside computers contain a layer that is only ten or so nanometers in width. But the goal of nanotechnologies is to produce actual devices at this scale.

9 For a more extended discussion of Hacking's entity realism, see chapter 1.

10 See Keller and Grantkowski (1983) for a historical analysis of the ways in which epistemology has been influenced by changing understandings of the nature of vision.

11 See chapter 4 for a more detailed discussion of Bohr's example. Eigler's metaphor is discussed further in chapter 1.

12 Some authors have suggested that while an epistemological economy based on the visual relies heavily on distal forms of knowing and representationalism, touch and proximal forms of knowing lend themselves to performative understandings in which the boundaries between body and object are not so easily mistaken as given. Note, however, that in this case, Eigler invokes proximal forms of knowing for the sake of making representationalist claims. This example provides a useful caution against such easy equations.

13 The journalist Robert Irion (2000) offered this comment in a different spirit

from my use of it here. He was actually referring to Eigler et al.'s "quantum mirage" in making this comment and the "ghostly" presence of nonentities in this micrograph. But I would argue that Magritte's refrain has a different valence and could justifiably be placed under any of the micrograph images, because his point is that representationalism is flawed (not that pipes don't exist or that they're merely "ghosts" of real things).

14 I am not drawing conclusions here on the basis of one example but using this and other examples in this final chapter to highlight some important points developed in the previous chapters.

15 Ira Flatow's interview with Don Eigler was a live broadcast, "Smallest Circuits," on *Talk of the Nation: Science Friday*, National Public Radio, November 1, 2002.

16 A nanometer is one billionth of a meter.

17 An IBM press release and animation are available on the Web, http://domino.research.ibm.com/comm/pr.nsf/pages/news.20021024_cascade.html.

18 This statistic is widely reported. This particular quote comes from www.nanotsunami.com. In 2004 George Bush signed a $3.7 billion nanotechnology funding package.

19 The quote is from Ratner and Ratner 2003, 108. One is left wondering about the scale of nanoscientists.

20 This quote and the passage quoted in the epigraph are from Neil Gross and Otis Port, "The Next Wave for Technology," *Business Week*, August 24–31, 1998.

21 From the PaxIT website. Benyus is a director of the California-based engineering company, whose chairman and CEO is Paul Hawkin, author of several books on sustainability and industry.

22 In an article for the *New York Times Magazine*, June 16, 2002, entitled "Got Silk," the writer Lawrence Osborne reports that Jeffrey Turner had this to say about his new creation: "You could call them Spidergoats," he says. "But that would give people misconceptions. They're only 1/70,000th spider, after all. When it comes down to it, they're just normal goats with one spider gene in them. They're just goats." He pauses. "Mostly."

23 The quote is from Lawrence Osborne, "Got Silk." Osborne notes that "One of [Nexia's] rivals, PPL Therapeutics, runs the farm in Scotland that collaborated in the production of the famous sheep clone, Dolly."

24 "Nexia and U.S. Army spin the world's first man-made spider silk performance fibers," January 17, 2002, http://www.eurekalert.org/pub_releases/2002-01/nbi-nau011102.php.

25 Turner, quoted in "Spinning a Tough but Silky Yarn," *SpaceDaily: Your Portal to Space*, January 22, 2002, http://www.spacedaily.com/news/materials-02a.html. See also Derek Reiber, "The Slippery Bioethics of Spinning Silk from Milk: Is Nexia Biotechnologies practicing biomimicry, or is it taking the burgeoning field in a dangerous new direction?" *TidePool*, June 24, 2002, http://www.tidepool.org/greentide/greent.6.24.02.cfm. Coauthored by scientists at Nexia Biotechnologies and the U.S. Army Soldier Biological Chemical Command, the technical details are published in Lazaris et al. 2002.

26 If OncoMouse™ is a patented laboratory tool, her kin, BioSteel® goats, are entire factories: "In the future, animals will be our factories . . . Very cheap factories" (Jeffrey Turner, quoted in Osborne, "Got Silk").

27 Janine Benyus, from the Boston Research Center interview, clip 9, "The Height of Hubris," available through the Biomimicry website, http://www.biomimicry.org.

28 The quote is from Benyus. The source is the Biomimicry website.

29 Friedrich Engels issued biting critiques of social Darwinism, exposing it as a poorly disguised ruse: "The whole Darwinist teaching of the struggle for existence is simply a transference from society to living nature of Hobbes's doctrine of 'bellum omnium contra omnes' and of the bourgeois-economic doctrine of competition together with Malthus's theory of population. When this conjurer's trick has been performed . . . the same theories are transferred back again from organic nature into history and now it is claimed that their validity as eternal laws of human society has been proved" (Friedrich Engels, in "Letter to Lavrov," November 12–17, 1875, cited in Lewontin et al. 1984, 309).

30 Janine Benyus, from the Boston Research Center interview, clip 8, "Seeing the 'Other' with Respect."

31 See Haraway 1997 for a more in-depth critique of the notion of "purity" and its problematic invocation by activists doing battle with genetic engineering projects. Haraway's astute assessment of this irony has unfortunately been badly misunderstood. It is a distortion of Haraway's argument to equate her critical assessment of the antibiotech activists' appropriation of the discourse of purity (which fits all too neatly with, and clearly feeds right into, contemporary anti-immigration and other neoconservative discourses) with an uncritical technophilic position; she is not saying that the concerns that these activists have expressed are consequently ill-founded; neither does the very fact that bioengineering destabilizes the nature-culture dualism thereby earn her unqualified endorsement. Rather, Haraway turns our attention to the key question: "what counts as nature, for whom, and at what costs" (1997, 104). Indeed, this is the central theme that runs throughout Haraway's work.

32 The *New York Times* article, written by Jonathan Abraham, was published on September 4, 2001. The reference for the scientific article is Aizenberg et al. 2001.

33 Quoted from John Whitefield, "Eyes in Their Stars: Engineers Envy Brittlestar Bones' Built-In Lenses," August 23, 2001, Nature News Service.

34 Photosensitive species of brittlestars exhibit responses to their environment that are superior to those of other marine organisms and seem to entail visual functioning. For example, they move out of the way of predators and run into crevices they spy from a distance. The existence of photosensitivity was linked to diffuse dermal receptors in previous studies.

35 R. Sambles quoted in Whitefield, "Eyes in Their Stars."

36 "Can We Learn to See Better from a Brittlestar?" BBC News Service, December 16, 2002.

37 Whitefield, "Eyes in Their Stars."

38 R. Sambles, "News and Views," *Nature* 412, no. 23 (August 2001): 783.

39 National Public Radio, August 22, 2001.

40 Maia Weinstock, "A Thousand Eyes without a Face," *Discover Magazine*, November 2001.

41 This is not to say that language, culture, technology, and labor don't matter; rather, the difficulty is the assumption that they serve a mediating function. Agential realism rejects the geometrical optics metaphor of lenses and mediation and specifies *how* these factors come to matter.

42 Don't forget that not everything that constitutes the phenomenon of the brittlestar is obviously connected to its body, though it is entangled with it! Examples of the ambiguity of bodily boundaries are discussed later.

43 This example of the brittlestar's discursive practices provides an illustration of the fact that intelligibility need not be a matter of intellection but rather more generally may entail differential responsiveness to what matters. See chapter 4.

44 This is not to suggest that materiality and discourse are therefore to be held as equivalent, but rather that the relationship is one of mutual entailment. Similarly, one cannot draw a distinction between the brittlestar's skeletal system and its visualizing system: there is no skeleton without the calcite crystals that also make up the visualizing system, and vice versa.

45 Haraway does not take location to be about fixed position (though unfortunately many readers who cite Haraway conflate her notion of "situated" with the specification of one's social location along a set of axes referencing one's identity). She reiterates this point in different ways throughout her work. For example, in "Situated Knowledges" she writes: "Feminist embodiment, then, is not about fixed location in a reified body, female or otherwise, but about nodes in fields, inflections in orientations, and responsibility for difference in material-semiotic fields of meaning. Embodiment is significant prosthesis; objectivity cannot be about fixed visions when what counts as an object is precisely what world history turns out to be about." Situated knowledge is not merely about knowing or seeing from somewhere (as in having a perspective) but about taking account of how the specific prosthetic embodiment of the technologically enhanced visualizing apparatus matters to practices of knowing. And if her use of the "@" sign in *Modest_Witness* can be understood as a mark of the specificity of location, then we can conclude that location is not equivalent to the local, but neither does the globality of the Net imply universality but rather points to its distributed and layered nature (1997, 121): "The '@' and '.' are the title's chief signifiers of the Net. An ordinary e-mail address specifies where the addressee is in a highly capitalized, transnationally sustained, machine language-mediated communications network that gives byte to the euphemisms of the 'global village.' Dependent upon a densely distributed array of local and regional nodes, e-mail is one of a powerful set of recent technologies that materially produce what is so blithely called 'global culture.' E-mail is one of the passage points—both distributed and obligatory—through which identities ebb and flow in the Net of technoscience" (Haraway 1997, 4; italics mine). Location, for Haraway, may be about the specification of where the addressee is *in* the Net, but the Net is not fixed, and neither are identities or spacetime. Though Haraway doesn't seem to go as far in making the ontological points I want to emphasize here, in both accounts it seems that while *location* cannot be about occupying a fixed position, it may be usefully (con)figured as *specific connectivity*. See chapter 4 on the agential realist conception of objectivity not as a view from somewhere but as a matter of accountability to marks on bodies. Objectivity is not solely an epistemological matter (a matter of seeing, albeit specifically embodied sight) but an ontological (ontoepistemological) one.

46 See chapters 4 and 7. Schrödinger nicely sums up the difficulty of the spectator theory of knowledge as follows: "Without being aware of it, and without being rigorously systematic about it, we exclude the subject of cognizance from the domain of nature that we endeavor to understand. We step with our own person back into the part of an onlooker who does not belong to the world which by this very procedure becomes an objective world" (Schrödinger [1944] 1967, 127).

47 Quantum phenomena suggest an ontology based on entanglement where relations take primacy over relata. See chapter 7 for more details. The issue here is not whether macroscopic entanglements at this scale have been observed; the issue is one of ontology, and as far as we know the world is not broken up into distinct regions each with different physical laws and realities.

48 This optical limit is called Abbe's law. In theory, the diffraction limit can be mitigated (i.e., the diffraction effects reduced) by taking advantage of certain features of the phenomenon of quantum entanglement, but a limit exists nonetheless for any finite number of entangled photons. See, for example, Boto et al. 2000, and also the cautionary comments in Steuernagel 2003.

49 The focus of the analysis in the *Nature* article is exclusively on geometrical optics; there is no discussion of possible physical optics effects, such as diffraction. Diffraction effects limit the resolving power of a lens. For a given wavelength of light, the smaller the lens size, the greater the blurring of the image by diffraction. This is an important factor for small animals such as insects. In fact, it is the reason they don't have the kind of eyes that the human or the octopus has. If the human eye were scaled down to fit an insect, the insect would be unable to resolve images because the diffraction effects would be very significant for a lens that small. So insects use a different optical system, namely, compound eyes. The compound eye is made up of many individual units called ommatidia. Each ommatidium is a simple light detector (a light pipe) that points in a different direction. The compound eye's ability to resolve images depends on a large number of small ommatidia: resolution increases the smaller and more numerous the ommatidia. But if the ommatidia are too small, then blurring caused by diffraction becomes significant. The optimal size of the ommatidia is a compromise between these competing effects.

That is, the optimal size for the individual ommatidia of a compound eye is a trade-off between the competing effects of angular resolution between neighboring lenses (which like pixels on a monitor have better resolution the smaller their size and greater their proximity [density]) and the limits of resolution due to diffraction effects of an individual lens (which increase the smaller the individual lens [pixel]). For example, for a wavelength of 0.5 microns (yellow-green), the optimal diameter of an ommatidium is 27 microns (see *Optima for Animals*, by R. McNeill Alexander [1996]). The individual lenses of the brittlestar have a diameter of approximately 20 microns, so it seems that the brittlestar has also engineered a good trade-off between resolvability and diffraction. For a discussion of the optics of the compound eye, see Feynman et al. 1964, vol. 1, chap. 36, p. 8.

50 This correspondence is a result of wave-particle duality. An explanation can be found in elementary textbooks on quantum physics. See, for example, Eisberg and Resnick 1974.

51 This phrase is Sandra Harding's (1991, 147), but she is not alone in this insistence.

52 Where "holding," "responding," and "thinking" are intra-active engagements with, and as parts of, specific configurations of the world.

53 Inanimate phenomena, like atoms, may seem to be altogether a very different matter. Descartes would have us imagine atoms as little things running in the void, and this conception seems to speak against any suggestion that atoms might engage in practices of recognition. But the notion that atoms are self-contained objects with inherent properties that follow deterministic trajectories is no longer viable. In Bohr's account, atoms are not simple objects but complex, open-ended configurations of intra-acting practices. That is, an atom includes the apparatus that helps constitute it. To take one example, surely there is some recognizable sense in which entangled particles taking part in a quantum teleportation experiment can be said to "recognize" one another, for they communicate well enough with one another to transmit information across the Danube River (see *Nature* and BBC articles, August 18, 2004). One might object that this example is a human contrivance, a mere artifact of special laboratory conditions. However, the goal of the experiment was in fact to get particles to participate in these ways *outside* the laboratory. But more to the point, atoms participate in the world's differential becoming as part of many different complexes of practices, so it isn't a question of attributing the capacity of recognition to atoms-in-isolation (which are mere abstractions). That is, the point that is often neglected but truly central to what is at issue here is that the larger material conditions are integral to what a phenomenon is, and this includes the "marks on bodies," that is, the traces of the enfolded processes of materialization, and an accounting of *how* this differential response matters. (By the way, this also means that the distinction between animate and inanimate can't be fixed along a line drawn between beings who have memory and those who don't. Electrons as phenomena carry the traces of their enfolded becoming within them, just like any other phenomena.) Or, as Rouse puts it: "The language of 'differential responsiveness' has been used to characterize non-normative relations (e.g., iron responds differentially to its environmental conditions by rusting or not rusting), in contrast with both instrumental rationality and semantic articulation. Of course, your response and mine is to say that the appearance of non-normativity has been achieved in the iron-rusting case (or in the examples you nicely bring in of the responsiveness of atoms to apparatus, or particles in a quantum teleportation phenomenon) by artificially drawing boundaries that set aside how this differential response matters" (private communication). Rouse provides an account of discursive practices in their materiality that shares many close affinities with my account. Rouse understands intelligibility in terms of inference rather than differential responsiveness, but he also expands and transforms the concept of inference in a way that moves it beyond its traditional human-based conception. I am indebted to Rouse for engaging and illuminating conversations on these matters.

54 See especially chapter 7.

55 See Haraway 1997 on the "nature of no nature" and the "culture of no culture" (the latter is borrowed from Traweek 1988).

56 In my thinking about temporality I have benefited from reading Astrid Schrader's remarkable writings on temporality and another sea creature called *Pfiesteria*, dinoflagellates (organisms that live in an indeterminate space between plants and animals) whose toxicity to fish depends on their material histories that are inseparable from the environment with which they are entangled. Schrader (2005) argues that understanding Pfiesteria as "ghostly"/spectral phenomena is necessary for creating responsible social policy concerning the dumping of waste products that produce Pfiesteria.

57 Indeed, this is an excellent reminder that the recent uncritical embrace of the new that is currently in vogue among certain critical theorists and their followers might well give us pause; for although in a certain sense there is nothing but the new, this point should not deflect our attention from the fact that the uncritical embrace of the new (the brighter, shinier, lighter model) fits all too comfortably with capitalism's reliance on the continual production of new desires and a desire for the new.

58 As I was putting the finishing touches on this book, the University of California, Santa Cruz, announced a new interdisciplinary research program included in the 2006 federal appropriations bill. The new program, the Bio-Info-Nano Research and Development Institute (BIN-RDI), is to be "a broad partnership of government, academia, and industry focusing on the convergence of biotechnology, information technology, and nanotechnology."

59 From the testimony of Dr. Ruzena Bajcsy, Assistant Director for Computer and Information Science and Engineering, National Science Foundation, before the House Basic Research Subcommittee hearing "Beyond Silicon Computing," September 12, 2000.

60 These agencies, as well as the National Science Foundation (NSF)—the one sponsor that we might naturally expect to support research on quantum entanglement—are mentioned in the testimony of Dr. Bajcsy, September 12, 2000.

61 This is not to say that physics departments are suddenly interested in the "philosophical" implications writ large. Rather, they are interested primarily in only those issues that break through the surface of the "metaphysical" realm into the physical world. A search of the Los Alamos Preprint Library (which archives all physics preprints, not only those produced at the Los Alamos National Labora-

tory) shows that the number of articles that have to do with quantum entanglement has increased from a handful in 1995 to more than five hundred in 2002.

62 See chapter 7 for a detailed consideration of the profound philosophical implications of quantum entanglement.

63 Like the idea of nanotechnologies, the idea of quantum computers can be traced back to the musings of the physicist Richard Feynman. Currently there are multiple proposals for making quantum computers. The approaches include individual atom manipulations using STMs and quantum dot fabrication using optical or electron lithography.

64 Testimony of Dr. Bajcsy, September 12, 2000.

65 Elizabeth K. Wilson, "Quantum Computers," *Chemical and Engineering News* 78, no. 45 (November 6, 2000): 35–39. The Centre for Quantum Computation (CQC) maintains a website, www.qubit.org, that gives a sense of this massive effort and provides links to many different aspects of the project including introductory through advanced tutorials.

66 From the "New Quantum Revolution" webpage of the National Science Foundation, http://www.nsf.gov/news/overviews/physics/physics_q02.jsp. The first commercially available quantum cryptography system, called the "Navajo Secure Gateway," is produced by MagiQ Technologies.

67 I highly recommend Mike Fortun's delightfully witty exploration of the question of responsibility and quantum entanglements entitled "Entangled States: Quantum Teleportation and the 'Willies.'" My thanks to Mike for sending me this article following my presentation of the material in this section at the 2001 Annual 4S (Society for the Social Studies of Science) meeting.

68 Genealogies, in Foucault's account, differ from historical narratives in that they are not a search for origins and do not presume the primacy of the consciousness of individual subjects, a linear progressive unfolding of events in history, the stability and continuity of events or the coherence, regularity, and uniformity of history. Genealogies do not seek to uncover the truth of the past but rather are interested in the conditions of possibility of truth making. In particular, genealogical analyses investigate rather than presume those notions that seem to be without a history (like truth, origins, and subjects). To the extent that Foucault presumes the presence of a past, or more generally the givenness of space and time, genealogy has been stopped short in its tracks. But genealogy need not, indeed must not, be limited to the space and time of the human, or humanist notions of space and time. I have argued that the very nature of the materiality of bodies (and not merely the "human" variety) as phenomena militates against such a limited conception of genealogy.

69 In "Reconceiving Scientific Literacy as Agential Literacy, or Learning to Intra-act Responsibly in the World" (Barad 2000b), I discuss the kind of expanded sense of literacy that objectivity requires, and the need to devise a responsible and responsive science pedagogy and approach to scientific training. See also the discussions on science pedagogy and literacy in Haraway 1997.

70 Vicki Kirby's *Telling Flesh* (1997) speaks to this as well.

71 See chapter 7, especially the discussion of the quantum eraser experiment.

Astrid Schrader (2006) reads agential realism and Derridean messianicity as kindred spirits in constructing a "spectrology" that is attentive to questions of justice in the responsible practice of science. Derrida's and Schrader's insistence on the necessity of attending to temporality-in-the-making, rather than taking for granted some idea of an externalized notion of time, as an essential part of an ongoing commitment to justice, speaks to the point I want to make here. As Derrida reminds us, "no justice seems possible . . . without the principle of responsibility, beyond all living present, within that which disjoins the living present, before the ghosts of those who are not yet born or are already dead, be they victims of war, political or other kinds of violence, nationalist, racist, colonialist, sexist, or other kinds of exterminations, victims of the oppressions of capitalist imperialism or any of the forms of totalitarianism" (Derrida 1994, xix).

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KAREN BARAD is a professor of feminist studies, philosophy, and history of consciousness at the University of California, Santa Cruz. She has a doctorate in theoretical particle physics.

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