# 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 unintelligi-

bility—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.
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> 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.
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> —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 essential-

ism. 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.