

Chapter 2

On the Possibility of Feminist Philosophy of Physics

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2.1 Introduction

Physics is, like all sciences, not simply a collection of theories about how the world works. Theories and models of the world obviously play a critical role in physics, but they do not fully define the science. Rather, physics is an activity done by human beings with their attendant values, interests, and cognitive biases, in a complex, noisy world that does not come to us “carved at its joints.” The dynamic nature of physics—the discovery, justification, negotiation, acceptance, and so on of its claims, models, experiments, and methods—cannot be captured through an exclusive focus on the static mathematical formulations of physical theories. Instead, we can more fruitfully think of physics, or arguably any science for that matter, as a set of practices, and more specifically, as a set of distinctively social, cognitive, and theoretical/methodological practices (Longino 1990).

Understanding science as practices, rather than theories or data, is certainly not novel to this chapter or even philosophy of physics. An emphasis on practice has been one of the most notable aspects of the recent “naturalistic turn” in general philosophy of science, in no small part due to the arguments of many feminist philosophers of science. Theories and models are important, but their presentation and structure often obscures key aspects of their history, motivation, and importance. Moreover, many of the most interesting activities in science take place outside of the traditional categories of theory and evidence. A major project of feminist philosophy of physics has been to shine a critical light on the social and cognitive practices in physics, and how those ultimately influence other aspects of the science.

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There are typically not sharp divisions between these three types of practices; for example, many of the social practices are presumably grounded in cognitive practices within each individual. Nonetheless, the trichotomy of social, cognitive, and theoretical/methodological (henceforth, just “TM”) practices can provide a useful way to approach and discuss the practices of physics. The social practices of a science are the interaction patterns among groups of scientists. Inquiry about those practices thus involves questions about the systematic inclusion or exclusion of particular individuals or groups from the community, as well as the social behaviors and norms that allow certain individuals or groups to flourish once in the community, perhaps at the expense of others. The social practices also include the group-level interaction dynamics at all levels, from small-group collaborations, up through lab groups, departments, and even whole sub-domains of physicists (e.g., those working on quantum mechanics). We explore many of the more pernicious social practices in physics in Sect. 2.3.1.

The cognitive practices are the “ways of thought” employed by individual physicists. Some of these practices have only a local impact, as when an individual physicist has an idiosyncratic way of solving a problem. Many of the cognitive practices have a larger impact, however, often because they are essentially social norms that have been internalized, and so change the individual’s thinking patterns. In particular, as we will see in Sect. 2.3.2, the cognitive practices in physics include many beliefs and expectations about the nature of knowledge, how it is constructed, and who has a privileged standing in the community. As a result, physicists interpret theories and data differently depending in part on whether the source conforms to those expectations. These cognitive practices obviously derive partially from the dominant social practices, but they have a local, individual impact directly on the physicists’ ways of thinking about and understanding the world.

Finally, the TM practices of a science are the theories, background assumptions, experimental and analysis methods, and knowledge claims of that science. These practices are, in many ways, the focus of “traditional” philosophy of science and philosophy of physics. They provide the foundations and metaphysical implications of the science itself, as well as “how things work” in this particular science. Some of these TM practices have a logical or mathematical justification (e.g., using a consistent, unbiased statistical estimator); others are more historically grounded or contingent (e.g., in psychology, the p -value for a null hypothesis statistical test to indicate a “real” or “significant” effect is usually taken to be 0.05). Contemporary philosophy of physics—much like contemporary philosophy of chemistry, biology, or psychology—purports to study the foundations of the science, and as we see in Sect. 2.2, these foundations are, in practice, almost exclusively understood to be TM practices. Philosophers of physics see their job as engaging in a normative analysis of the TM practices. These analyses might be informed by descriptive findings, but typically only descriptions that outline the expected or permissible “moves” in the science. There is little impact of the detailed, culturally grounded descriptions of social and cognitive practices that are done by sociologists, anthropologists, and ethnographers of science. One of the key impacts of feminist philosophy of physics is precisely to shine a normative light on the social and

cognitive practices of physics, which can thereby enable us to better understand and critique the TM practices themselves. But first, we begin by looking at the types of questions normally asked in philosophy of physics.

2.2 Contemporary Philosophy of Physics

The research areas of contemporary philosophy of physics can be divided roughly into three categories, although the work of some philosophers can fall onto more than one. The first is exploring the metaphysical implications of our current theories; the second is providing rigorous proofs concerning philosophically interesting topics; and the third is analyzing particular events in the history of physics that shed light on current philosophical topics.

2.2.1 *Metaphysical Implications*

The first area concerns the metaphysical implications of our current theories; that is, saying what it is that our theories are telling us about what the world is really like. One large sub-area of this research is into the correct, or at least, an understandable, interpretation of quantum mechanics. I explain this example in more detail than the others because it will facilitate the comparison with feminist philosophy of physics later.

There are well-established and mathematically equivalent formalisms that we can use to make predictions about quantum mechanical systems, and these predictions have been shown to be highly accurate. The mathematical formalism does not, however, provide an interpretation of the variables in the equations; the mathematical functions alone do not say how they map or correspond to parts of the world. Consider, for example, the time-dependent Schrödinger equation for a non-relativistic particle:

$$i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{r}, t) = \left[\frac{-\hbar^2}{2m} \nabla^2 + V(\mathbf{r}, t) \right] \Psi(\mathbf{r}, t) \quad (2.1)$$

where \hbar is Planck's constant, \mathbf{r} is the position in 3-dimensional space, and Ψ is the wave-function. This equation is supposed to govern all particles—like electrons, protons, and photons—that are the constituents of all of the physical matter in the universe. But how does this equation govern particles? Each particle has a different wave function associated with each of the different aspects of it that can be measured. The equation above describes a particle's position, but for any given particle, there is a wave function for its momentum, its polarization, its spin, etc.

At a purely mathematical level, each wave function characterizes each (corresponding) property of the particle, including the possible changes in that property over time. Let's use a simple example: electron spin. The electron isn't actually spinning, but it behaves as though it is spinning about an axis. We can measure the spin of an electron, and there are only two possible values: we will either measure it to be "spin-up" (i.e., as if it were spinning counter-clockwise looking down the axis) or measure it to be "spin-down" (spinning clockwise). The spin wave function for the electron tells us how probable it is that our measurement will come out "spin-up" or "spin-down." And in the particular case of electron spin, the corresponding wave function says that these probabilities do not (in the absence of a measurement) change over time. For example, if the electron has just been stripped from an atom the probability is $1/2$, meaning that we have a 50 % chance of measuring it to be "spin-up" and a 50 % chance of measuring it to be "spin-down." If, however, we know the electron is "spin-up," then we have a 100 % chance of measuring it to be "spin-up" and a 0 % chance of measuring it to be "spin-down." More generally, if we take the absolute value of the square of the wave function (for position, momentum, spin, etc.) at any time, we will get a probability, for each of the possible states it could be in, of measuring the particle to be in that state.

Actually, since the electron behaves as though it is spinning along an axis, we can measure the spin of an electron along any dimension. If you think of the axis of the electron as being along the x -axis, our measurement of its spin will either be "spin-up _{x} " or "spin-down _{x} ." We could instead obtain these measurements for the y -axis, the z -axis, and any axis in between. We cannot, however, measure the spin in along the x -axis *at the same time* we measure its spin along the z -axis. One problem that seems unique to, or at least amplified by, quantum mechanics is what happens when we perform these measurements in a series. Recall that if we measure the spin of the electron along the x -axis to be, for example, spin-up _{x} , then measuring it along the x -axis again is guaranteed to result in a measurement of spin-up _{x} . However, if we measure the spin along the x -axis to be spin-up _{x} , and then measure it along the z -axis, and then measure it along the x -axis again, there is only a 50 % chance that the result of the third measurement will be spin-up _{x} . It is as if we'd observed a person's hair color to be brown, and then observed that person's skin color, and then had no idea what the person's hair color would be if we observed it again!

So how do we make sense of this very strange mathematics that nonetheless gives the most accurate predictions of the world at the quantum level? Here's where philosophers of physics have stepped in.¹ The standard interpretation of quantum mechanics was developed primarily by the physicists who invented it: Neils Bohr, Werner Heisenberg, and Max Born (Cushing 1994). This interpretation is the one that is presented in nearly all of the quantum mechanics textbooks for the past

¹At the advent of the new quantum theory the philosophers of physics were the physicists themselves. In the past 50–60 years, however, interpreting quantum mechanics has shifted to those in philosophy departments, and "real" physicists have largely ceased to concern themselves with these issues.

century (Griffiths 2004; Messiah 1999; see Sakurai 1994). According to the standard interpretation, before the first measurement occurs in our scenario, the wave function of the particle is in a *superposition* of being spin-up_x and being spin-down_x; that is, the particle is, in some sense, simultaneously in these two states. The oddness of superposition is popularly exemplified by Schrödinger's Cat that is (again, in some sense) simultaneously alive and dead. This superposition disappears once we make the measurement, however, as the wave function "collapses" to being just spin-up_x. At the same time, being in just spin-up_x is the same as being in a superposition of being spin-up_z and being spin-down_z. Thus, when we measure the spin along the z-axis, there is a 50 % chance of measuring it to be "spin-up_z" and a 50 % chance of measuring it to be "spin-down_z." Measuring the particle to be one or the other, say spin-up_z, "collapses" the spin wave function along the z-axis states, so the particle thereby goes back into a superposition of being spin-up_x and being spin-down_x, so the chances of it being measured again to be spin-up_x are back to 50 %. This idea that measurements collapse the wave function in a relatively "memory-less" way is absolutely central to the standard interpretation.

So, there are two questions for the standard interpretation: (1) what constitutes a measurement? And (2) what is the metaphysical status of the wave function? The first question is important because it seems now that the Schrödinger equation does not tell us how the wave function changes all the time: when there is a measurement, something happens to the wave function (the "collapse") that is not a part of the Schrödinger equation. Thus, on this interpretation, there is something very special about measurement and a complete theory should give a precise and detailed description of what constitutes a measurement.

The second question is important because, upon measurement, the wave function changes dramatically, and seemingly instantaneously. If the wave function is nothing more than a mathematical tool for producing probabilities or something that measures our knowledge, then there is no cause for concern. However, we have reason to think that the wave function is not just a conceptual tool, but rather is a real thing in the world that interacts with physical objects. First, as we just discussed, the apparatus for measuring the spin of the electron is itself physical, and the wave function seemingly changes because of an interaction with that physical thing. Second, postulating that the wave function can interfere with itself, like water waves can, explains the results of some very basic experiments with both light and particles (e.g., the one-slit and two-slit experiments). We initially thought we were talking about how just an electron behaves, but now it seems that we are talking about the behavior of both the particle and the wave function. Even worse, if the electron has a wave function for each of the possible measurements we could perform on it, then talking about a single particle actually means talking about a multitude, possibly an infinity, of different wave functions.

The standard interpretation is relatively silent about the status of the wave function and what constitutes a measurement, but many answers have been offered in different (non-standard) interpretations of quantum mechanics. Two of the most famous are from David Bohm and Hugh Everett. David Bohm's "pilot wave" theory (Bohm 1952; Cushing 1994) says there are two things—the wave and the

particle—and the wave guides the particle like an ocean wave guides a surfer. Hugh Everett’s “many-worlds” theory (Everett 1957; Maudlin 2011) says that when a measurement is made, the world branches into however many possible values the variable could have had, and that in each world a different value was obtained by the measurement. Other, less prominent interpretations include the “consistent histories” theory (Griffiths 2002; Omnes 1999), the “many minds” theory (Albert and Loewer 1988), the “relational” interpretation (Rovelli 1996), and the “Ithaca” interpretation (Mermin 1998). The core issue for philosophers of physics is how, if at all, to coherently understand and interpret the mathematics of quantum mechanics. That is, the focus is almost entirely on particular TM practices.

There are many other sub-areas of research into the metaphysical interpretation of our theories. Probability plays a key role in both quantum and statistical mechanics (i.e., the study of the behavior of large collections of particles). There are many different possible interpretations of probability, which can be roughly divided into objectivist and subjectivist. Interpretations of quantum mechanics often concern the ontological status of those probabilities. Probabilities also play an ambiguous role in the description of, and explanations for, the world given by statistical mechanics (Albert 2000; Ehrenfest and Ehrenfest 1959; Sklar 1995). Einstein’s special and general theories of relativity also prompt a number of different questions. For example, there are issues about the real difference between inertial and non-inertial reference frames, and the equivalence of inertial mass and gravitational mass (Cassirer 1957; Earman 1995; Reichenbach 1958). There are also important epistemological and ontological questions concerning the nature and foundations of space and time themselves (Friedman 1986; Sklar 1977).

2.2.2 *Proofs*

The second broad area in philosophy of physics is providing rigorous proofs concerning philosophically interesting topics, such as time travel, determinism, probability, and the curvature of space. For example, David Malament has attempted to prove that simultaneity in special relativity is not conventional (Malament 1977; Sarkar and Stachel 1999); Jeffrey Bub and Rob Clifton proved that it is possible to associate a classical probability space with a quantum state (Bub and Clifton 1996; Bub et al. 2000); John Manchak proved that a time machine of the type proposed by John Earman, Christopher Smeenk, and Christian Wüthrich is actually possible (Earman et al. 2009; Manchak 2009); Jantzen (2011) proved that any permutation invariant theory is incompatible with a particle ontology; and Werndl (2009, 2011) proved that there are deterministic and indeterministic systems that produce the same observations. In some cases, these proofs focus on implications of the physics that are not necessarily of interest to “mainstream” physicists. In many other cases, however, these proofs blur the line between philosophy of physics and physics proper. In all cases, though, they contribute to our understanding of the TM practices.

2.2.3 History and Philosophy of Physics

A final broad area in philosophy of physics is the analysis of particular events in the history of physics that shed light on current philosophical topics like scientific explanation, confirmation, and progress. For example, Earman and Glymour (1980a, b) have argued that neither the 1919 observations of the eclipse nor the measurements of the red shift provided the unequivocal support for Einstein's theory of relativity, as so often has been assumed by both physicists and philosophers; Norton (2011) has used two case studies from the confirmation of two of Einstein's theories to draw general lessons about the material theory of induction; Jammer (1966) has produced a very thorough account of the development of Quantum Mechanics that provides an incredible insight into the actual practice of science, rather than the ahistorical treatments that scientific developments often receive in textbooks; and Torretti (2000) uses a survey of mathematical modeling by Galileo, Newton and others to support his skeptical view of the (current) standard cosmological model.

2.3 Feminist Philosophy of Physics

Feminist philosophy of physics encompasses many different questions, but often starts with the observation that women are highly under-represented in physics, even compared to other sciences. The dearth of women has been well-documented for decades (European Commission 2006; Megaw 1992), and is an obvious entry point for much feminist philosophy of physics. One can ask about the impact of the underrepresentation of women on the social, cognitive, and TM practices of physics. Perhaps more interestingly, one can try to determine the reasons for the relative absence of women in physics, and then ask how those underlying factors change or harm physics itself. In this section, we start by considering these issues with respect to the social, cognitive, and TM practices, but also use them as a launching point for other questions and challenges that emerge in feminist philosophy of physics.

2.3.1 Social Practices

In the first place, students in physics (as well as other sciences) are told that science is the way to rid oneself of prejudices, feelings, and particular viewpoints to discover the truth about the nature of an independent reality. What students actually get, however, is very different. Women, in particular, are often acutely aware that prejudices and feelings do not get checked at the door of the science classroom or lab. This is part of the "chilly" climate that is mentioned in many analyses of the lack of women in physics: sexist language, disparaging remarks, lack of

encouragement, inappropriate allusions to one's gender in academic contexts, and outright sexual harassment (Rolin 2008). For example, when women are asked why there are so few women in science, they cite the unpleasantness of male dominated work places, both in the overt sexist behavior of men and the more subtle ways that women are ignored or sidelined (Ecklund et al. 2012).

In addition, there is a broad sociocultural perception among scientists that masculinity, in whatever form it manifests, is required to be a successful scientist, including success in physics (Urry 2008). For example, sociologist of science Merton (1957) tells his readers of the fierce competition to be recognized as the first one to discover some new phenomenon or theory. And prominent biologist Lewontin (1980: 186) claims that, "science is a form of competitive and aggressive activity, a contest of man against man that provides knowledge as a side-product."

In quite overt demonstrations of this assumption of masculinity, prominent women scientists in history have been described as being "manly." Dorothea Erxleben, one of the first women in Germany to earn a degree in medicine, was said to have "proven herself manly;" Emilie du Chatelet, the French translator of Newton's *Principia*, was praised by Voltaire as being a woman who was "a very great man;" and astrophysicist Cecilia Payne Gaposchkin was described by Edwin Hubble as "the best man at Harvard" (Bug 2000).

The identification of good science with masculinity even appears in other cultures. In *Beamtimes and Lifetimes*, Sharon Traweek compares the cultures of high-energy physics in the United States and Japan. The qualities that the Americans attach to the concept of a good, successful physicist are opposite to the qualities that the Japanese attach to the concept. In both cases, however, the qualities associated with the good physicist are the qualities that are taken to be masculine in the respective culture (Traweek 1988, 1992). American physicists value culturally masculine traits such as individualism, competition, bravado, and self-promotion. Japanese physicists, on the other hand, value quite different traits—cooperation, humility and inter-dependence—but they are again the ones that professional Japanese men, but not professional Japanese women, are taken to have (Traweek 1988).

There are often more subtle ways that women may feel unwelcome in physics, including the language and metaphors used by scientists to describe what science is. Nature is generally referred to as female, and often having secrets she doesn't want to give away. Merchant (1982) describes this powerful image of science as the "identification of nature with the female, especially a female harbouring secrets." Additionally, as Easlea (1986: 140) points out,

Images of male scientists investigating female nature have abounded in modern science from the time of Francis Bacon onwards, ranging from quite ferocious images of putting nature on the rack and torturing her secrets from her, together with images of unveiling, piercing and particularly of penetrating the secrets of female nature, to gentle, loving images of male wooing of a wondrous, if coy, female nature.

The physicist, typically a man, speaks of science as a dance, a marriage, a seduction, or an assault (Harding 1986, 1991). For example, Richard Feynman, one

hero of the physics community, says, “I am going to tell you what nature behaves like. If you simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing” (Feynman 1965: 129). In 1984, high-energy physicist Frank Close explain to the readers of *The Guardian* that “[s]he [nature] has cleverly hidden some of her secrets from view in the macroscopic world. [...] By probing nature at the cutting edge may we have our eyes opened to her greater glory” (Easlea 1986).

Indeed, the image of science as man’s quest to dominate nature has been widespread at least since Francis Bacon wrote *The Masculine Birth of Time* in the 16th century, but has been particularly salient in the physics community in the past hundred years. Since World War II, as American physicists became famous for developing the nuclear weapons that would end the war, physics has become very closely associated with the military (Easlea 1987). Dyson (1984) puts military scientists in the category of “nuclear warriors,” and cites the competition between physicists as a major driving force behind nuclear proliferation. In the wake of the Second World War, strategists at RAND and the U.S. Air Force Strategic Air Command (SAC) competed to devise a strategy to attack the Soviet Union. Herman Kahn, one of the strategists, “coined the term ‘wargasm’ to describe the all-out ‘orgiastic spasm of destruction’ that the SAC generals supposedly favored” (Easlea 2002: 107).

If women and girls in the Western world are socialized from a young age to project “feminine” attributes such as caring, humility, and cooperation, then it is no wonder that they might feel out of place in a social arena that not only values masculine traits above feminine ones, but also encourages the domination of the feminine by the masculine to the point of orgiastic destruction. Indeed, research shows a decline in girls’ participation in science, especially physics, starting in high school (Kahle 1987; Weinreich-Haste 1986). This research suggests that there is more going on than mere lack of interest (Danielsson 2010).

So, despite the fact that, when asked why there are so few women in science, *men* tend cite innate differences in scientific and mathematical ability (Ecklund et al. 2012), we need not postulate any cognitive differences to explain why so few women choose to become physicists. In fact, there is ample evidence that there are not any differences between men and women in the relevant cognitive abilities, such as mathematical cognition (Spelke 2005). But even if there are not relevant cognitive differences between men and women, we must still investigate the cognitive practices of physics, and consider how they may be hindering the success of women who do become physicists.

2.3.2 *Cognitive Practices*

Cognitive practices in science most obviously include the ways in which knowledge is constructed and achieved by particular scientists. Equally importantly, these cognitive practices also include the ways in which scientists *think* or *expect*

knowledge to be constructed. These background beliefs about the processes and practices that can possibly lead to knowledge can be quite specific and stringent. As a result, many types of argument and investigation are declared simply irrelevant, and so people who prefer those modes of reasoning will be excluded or marginalized from the physics community. There is ample evidence that these cognitive practices, and expectations about those practices, are part of the explanation for the relative dearth of women in physics. Moreover, these expectations are particularly problematic because they *mischaracterize* the ways in which physics (at least, modern-day physics) is actually done. Before considering the ways in which the expectations are mistaken, however, we first examine the cognitive practices and expectations themselves, with a particular focus on their impact on women's ability to enter and succeed in physics.

2.3.2.1 Who Can Be a Physicist? Who Can Construct Knowledge About Physics?

Historically, women have been systematically marginalized in physics, thereby creating biased expectations about who can contribute the production and construction of knowledge about physics. In fact, theories from physics were sometimes used (incorrectly, of course) to justify this exclusion. For example, according to physicist and educator Heinsohn (2000), some physicists in the late 19th century used the principle of energy conservation to argue that women could not both pursue a rigorous intellectual career and have strong, healthy babies. These arguments were ostensibly to prevent rivalry between men and women, but had the effect of making it harder for women to participate in the community of physicists. Similarly, according to Holland (2006), the foremost translator of 18th century German physicist Johann Wilhelm Ritter's scientific works, Ritter used concepts from the study of magnetism, namely polarization and indifference, to explain the "natural" longing women have to become pregnant and give birth. Even when women were able to participate in physics, their contributions were systematically devalued or relegated to mere technical improvements (Bug 2000; Shapin 1994).

These historical practices have been exacerbated by many features of physics pedagogy and the perception of physics in the wider culture, as these further reinforce the idea that only men can be successful physicists. Physics textbooks are notorious for giving the impression that the history of physics has been a linear development of great discoveries made by solitary gentlemen scientists. There are often boxed vignettes featuring a short biography and picture of the many famous (male) physicists including Galileo, Newton, Maxwell, Einstein, Bohr, and more recently Feynman (Danielsson 2010; Traweek 1988). The popular history of physics similarly focuses on the "great men" who are held to be responsible for modern-day physics. In fact, even small children nearly exclusively identify and portray scientists as male (Kahle 1987), with this effect diminishing only slightly as the child's age increases (Bug 2000). Unsurprisingly, people regard themselves as

less able to contribute to an enterprise when the history of that enterprise does not include members of their group (Bug 2000).

All of these different factors lead to the expectation that successful physicists must be solitary, male geniuses, who construct new theories and knowledge by the sheer force of their own personal intellects. Many different types of individuals—most importantly (though not exclusively), women—are simply not expected sources of physics knowledge. The internalization of those cognitive expectations leads to increased (implicit) discrimination, reduced participation, and less chance for success (Schiebinger 2008). For example, studies show that both men and women rate the quality of a journal article higher when they believe the author is a man (Goldberg 1968; Paludi and Strayer 1985). Additional studies show that both women and men rate the quality of the curricula vitae of candidates for hiring or review higher if they believe that the candidate is a man (Foschi 2000; Steinpreis et al. 1999). One reason may be that women who succeed at jobs that have historically been male are judged to be less likable and have been more denigrated than similarly successful men (Heilman et al. 2004).

The internalization of these cognitive expectations not only excludes people from the domain of physics, but also can potentially eliminate various ways of knowing and knowledge construction. If knowledge is expected to be the product of a solitary genius, for example, then the results of collaboration will face a higher evidential and argumentative bar, simply because they do not conform to the dominant expectations. Moreover, these expectations not only lead to the exclusion and ignorance of women's contributions to physics, they also belie the reality that modern-day physics is actually practiced and constructed by communities of scientists working in close collaboration with each other.

2.3.2.2 Actual Practice Versus Expectations in Physics

As just noted, the dominant cognitive expectations about knowledge creators and constructors in physics is that they are solitary male investigators, engaged in the dispassionate, value-free quest for objective truths (Danielsson 2009; Keller 1985; Schiebinger 2008). As a result, people who violate these expectations—e.g., by being a woman, or passionate about the science, or working in a collaborative—are assumed to be (much) less likely to be producing or constructing knowledge. These pernicious effects are a significant harm on their own, but matters are made even worse because the expectations are actually false: the social, cognitive, and TM practices of modern-day physics simply do not conform to this model. Instead, modern-day physics involves passionate scientists working collaboratively to develop, articulate, and defend their preferred views using both evidential and value-laden grounds, all with the goal of constructing knowledge about the world. Physics is not a dispassionate mirroring of the world, but requires imagination and creativity (Easley 2002). Indeed, research shows that physics teachers are explicit about the expectations of serious, dispassionate work, but nonetheless reward male behavior in the classroom and lab that is playful and imaginative (Hasse 2002).

One of the most important divergences between expectations and reality can be seen vividly through the lens of feminist philosophy of physics, inspired by broader observations in feminist philosophy of science. The standard belief is that physicists are engaged in the search for objective truths; for example, physics is understood as trying to find the “language” of the universe, or to establish truths that are independent of our particular, situated experience. There is thus no need for debate, discussion, or negotiation; we ought, on this picture, simply calculate (in our theories) and compare (with experimental results). One of the central insights of feminist philosophy of science has been the impossibility of such an Archimedean point that stands outside our own cognition and ways of knowing (Kitcher 2001). Claims that are held up as “objective” are actually “socially negotiated” (Longino 1990) and “partial and situated knowledge” (Haraway 1990: 183–202) that emerges only through the interactions of particular individuals with particular cultural, social, and cognitive values (Harding 1991).

In the context of physics, these observations reveal the importance of interaction and culture in the construction of knowledge. We cannot adopt a “view from nowhere,” but rather must ask questions from our actual value-laden, goal-driven position. To use just one example, Robert Boyle’s gas law and the science that surrounds it must be understood as emerging in part from the sociocultural milieu and circumstances in which he lived and investigated (Potter 1993, 2001; Shapin and Schaffer 1985). Moreover, the inevitable use of goals and values in science does not thereby make the science “bad” or wrong; matters are far more complex. A diversity of approaches and the need for negotiation in scientific contexts can lead to substantially better science. The particular challenge for women in physics is that these goals and values can be influenced by gender ideologies in ways that lead women to be less likely to join and contribute to the physics community (Rolin 1999).

Moreover, women who manage to enter physics suffer further from these divergences between expectations and reality. Women, in part simply by being women, do not conform to the dominant expectations about who can be a successful physicist, and so their research is systematically devalued. Women who do essentially the same work as men—both amount and quality—are perceived to be less competent and credible than their male counterparts (Traweek 1988), and receive less support from the broader community (Taylor 2010). In general, the results of their work is not trusted as much as if a man did the same work (Taylor 2010). These judgments even seep into female physicists’ own self-perceptions, as their self-assessments undervalue their own work, relative to the work of male physicists (Correll 2001, 2004; Fiorentine and Cole 1992).

These biased, discriminatory cognitive practices—some employed by both men and women—are obviously closely related to the pernicious social practices from Sect. 2.3.1. Many of the cognitive practices can naturally be understood as internalized versions of the broader, more explicit social practices. And these cognitive practices have a similar impact on the science of physics: by excluding or devaluing the work of talented, capable members of particular group(s), the scientific community inevitably suffers in a multitude of ways. That being said, one might object

that these practices only impede our progress in physics, rather than actually harming the science. That is, perhaps these practices, while socially and personally harmful, only lead to slower science, not worse science. This response is, however, based on wishful thinking about the possibility of the isolability of the TM practices from the social and cognitive ones, as we shall see in the next section.

2.3.3 *Theoretical/Methodological Practices*

Hardly anyone working in science or studying science today would challenge the claim that there is sex and gender bias in the work place and culture of physics; nonetheless, very few would say that this bias spills over into the actual results of physics. These kinds of biases may affect medicine, biology and other “soft” sciences in which people are the objects of research, but surely there can be no gender bias in the curvature of spacetime or the energy level of a particle, right? Urry (2008: 150), for example, argues that since photons (and other objects of study for physicists) are not gendered, “there is little freedom in—and certainly no gender-related influence on—the results of experiments or the interpretation of observations of the natural world.” In addition, she says:

The laws of physics simply know no gender. What gets studied has little or no relation to gender, with possible exceptions in applied areas. Here physics and astronomy and mathematics are very different from, say, archaeology or anthropology or biology, where gender is part of what is being studied (Urry 2008: 151).

But Urry’s claims here are off the mark; as physicist Whitten (1996: 13) remarks, feminist science studies is *not* saying that her “scattering code produces different output because [she is] female”. Rather, the claim is that gender can influence physicists’ goals and values, and that we should thereby expect at least some (indirect) influence of gender on the results. This line of argument is pursued by Karen Barad, who offers a metaphysical interpretation of quantum mechanics that takes into account not only the views of the theory’s creators, but also much recent research in feminist science studies (see, e.g., Barad 1995, 1996, 1999, 2007).

Like most philosophers of physics, Barad is concerned with understanding the metaphysical implications of our best physical theories. With quantum mechanics, she approaches this in several ways. She begins with Niels Bohr and his views about the nature of reality and the practice of science,² and builds an interpretation of quantum mechanics consistent with, but going much further beyond, these views. She explains how this interpretation is, on the one hand, realist and objective, and on the other hand, is inspired by and consistent with the general themes of feminist epistemology. Finally, she gives an account of one way that physics education

²As the point of Barad’s account is not to provide a definitive interpretation of Bohr’s philosophy, but only to use some of his well known views to create her own interpretation of quantum mechanics, I will not comment on the accuracy of her description of Bohr’s views.

reinforces the misrepresentation of physics as a TM practice, which has the side effect of driving many people away from the discipline.

In most of her writing, Barad emphasizes the fact that the way the Heisenberg Uncertainty Principle is presented to students in lectures and textbooks is contrary to the way that Bohr conceived of the principle, and in fact contrary to the way Werner Heisenberg himself came to view it after discussions with Bohr (Murdoch 1987). The Uncertainty Principle, mathematically, is the relationship between the accuracy of the value of two complementary observables. Consider the position, x , and momentum, p , of a quantum particle. When we measure the particle's position, there is some error in that measurement, Δx . But then consider that, in measuring the position—by shining a light on it, for example—we necessarily change the particle's momentum by some amount. If we had a value for the momentum before, then that value has been changed (by the act of measuring the position) by Δp . The Uncertainty Principle says that no matter how hard we try, there is a limit on the amount we can reduce the error in either measurement, and that limit is given by the equation:

$$\Delta x \Delta p \geq \hbar/2 \quad (2.2)$$

Heisenberg's principle is usually explained by appealing to what we can *know* about the particle: if Δx is the uncertainty in our knowledge of its position and Δp is the uncertainty in our knowledge of its momentum, then our certainty about both quantities at the same time is limited by Heisenberg's equation.

However, this is not the right way to think about it, according to Bohr. Bohr thought a more accurate name for the principle would be the "Indefiniteness Principle" or something similar. His view is that there are certain sets of observables, like position and momentum, that are complementary, meaning not that the values cannot just both be *known* at the same time, but that the particle does not actually *have* definite values for both at the same time. The equation tells us that the more definite the value for position is, the more indefinite the value for momentum becomes, and vice versa. Thus, if a particle has an absolutely definite momentum, then the indefiniteness of its position would be infinite, meaning that the particle could literally be anywhere at all! Bohr and Heisenberg debated the epistemological and metaphysical interpretations of the Uncertainty Principle, until Bohr won Heisenberg over.

What this means is that measurement has a very prominent role in Bohr's interpretation of quantum mechanics, as we saw when we earlier discussed the standard interpretation. According to Bohr, all that we can know are the results of our measurements, and the measurements are merely interactions between a quantum system and a non-quantum (macroscopic) system. And not only is that all we can know, but that is all there is to know. In Bohr's view quantum mechanics is nothing other than an apparatus for making predictions about the outcomes of measurements. The outcomes of measurements are what Bohr calls "phenomena" in his later writings, where he insists that phenomena *are* reality.

To make this clearer, let's contrast this Bohrian view of science and experiment with the classical (Newtonian) view. In a classical (Newtonian) worldview, science is objective because

1. there is a clear distinction between the observer and the observed,
2. the objects of study have properties that are independent of the particular observer,
3. science aims to describe this observer-independent reality,
4. measurements are reproducible, and so free of bias, and
5. measurements are continuous and determinable, and so can be subtracted out when describing reality.

In contrast, on Bohr's view, science is objective because

1. the material apparatus required to make the measurements is what defines the concepts,
2. phenomena constitute reality,
3. measurements are reproductions of phenomena,
4. measurements are reproducible by the same configuration of material parts and experimental conditions, and
5. scientific theories describe this new conception of reality.

For Bohr, it isn't that an electron has a spin, and we send it through a measuring apparatus so that we can know what this spin is. Rather, for Bohr, it doesn't make sense to talk about any properties of particles in a context other than that of measurement. So what is real for Bohr is not that the electron is spin-up along the x-direction, for example; what is real is the phenomenon of our measuring apparatus interacting with the electron and producing the measurement spin-up along the x-direction. For Bohr, there is no observer-independent reality: reality is just the phenomena, and so is very much observer-dependent.

To describe this alternative conception of what is real, Barad introduces the term "agential reality," and describes her version of Bohr's philosophy of science as "agential realism." This new phrase is meant to convey a whole host of philosophical positions that are essentially feminist in their origin. She draws on the theories of Haraway (1990), Keller (1985), Harding (1986, 1991), Longino (1990), and Latour (1993) to identify the ways in which agential realism is a feminist philosophy of science. The most prominent ways in which this is true are the following:

1. Agential realism grounds and situates knowledge claims in local experiences: objectivity is literally embodied [...] objective knowledge is situated knowledge,
2. Agential realism privileges neither the material nor the cultural: the apparatus of bodily production is material-cultural, and so is agential reality [...] the apparatus [...] is not separable from phenomena,
3. Agential realism entails the interrogation of boundaries and critical reflexivity [...] phenomena are the embodiment of cultural practices within theory, and
4. Agential realism underlines the necessity of an ethics of knowing (Barad 1996: 179).

One of the most important aspects of agential realism concerns the notion of objectivity. Ordinary scientific realism contrasts objectivity with subjectivity. In the first place, objects of study are said to have objective properties, which are properties that the object possesses prior to any observation. These objects may also have subjective properties, which are the properties that a person attributes to the object upon interaction with the object. In the practice of science, “being objective” means setting aside or ignoring all together any subjective properties, and instead concentrating on discovering the objective properties of an object. The way to determine whether a scientist is being objective or has discovered an objective property is to ask whether another scientist can repeat that discovery (the observation, the experiment, etc.).

Agential realism dissolves the conceptual difference between objectivity and subjectivity with the claim that phenomena are the only reality. On this view, objects don’t possess any properties that are independent of their interactions with other objects in the world. Rather, the *only* properties objects have are those that arise during these interactions. Thus, there can be no difference between objective and subjective properties. How, then, can we still claim that science is objective? The idea is that, under the same conditions—the same measuring apparatus, the same objects, and an observer—the observers will always witness the same phenomenon. As Barad (2007: 361) explains:

In my agential realist account, scientific practices do not reveal what is already there; rather, what is “disclosed” is the effect of the intra-active engagements of our participation with/in and as part of the world’s differential becoming. Which is not to say that humans are the condition of possibility for the existence of phenomena. Phenomena do not require cognizing minds for their existence; on the contrary, “minds” are themselves material phenomena that emerge through specific intra-actions. Phenomena are real material beings. What is made manifest through technoscientific practices is an expression of the objective existence of particular material phenomena. This is, after all, a realist conception of scientific practices. But unlike in traditional conceptions of realism, “objectivity” is not pre-existence (in the ontological sense) or the preexistent made manifest to the cognitive mind (in the epistemological sense). Objectivity is a matter of accountability for what materializes, for what comes to be. It matters which cuts are enacted: different cuts enact different materialized becomings.

Ultimately, Barad takes herself to be engaged in the same kind of project as the philosophers of physics described in Sect. 2.2.1. She is presenting an argument “that agential realism can in fact be understood as a legitimate interpretation of quantum mechanics” (Barad 2007: 94). She is exploring the metaphysical implications of the mathematical formalism of quantum mechanics—i.e. trying to understand what quantum physics tells us about the way our world really works—so that we can improve our TM practices in physics.

2.4 Open Areas of Research in Feminist Philosophy of Physics

I want to close this chapter by indicating some areas of research in feminist philosophy of physics that are underdeveloped. The case of Barad's interpretation of quantum mechanics is the only one I know of that provides a feminist analysis of the TM practice of physics. The interpretation of quantum mechanics is an active area of research in philosophy of physics, and perhaps more feminist analysis could be done there. Other areas in which no one has ventured a feminist analysis are the interpretation of probability in physics, interpretations of special and general relativity, and theories of the foundations of space and time.

There are several feminist analyses of the cognitive practice of science, but analyses of knowledge production in physics are few. One excellent example, though, is Rolin (1999: 512) who argues that it is conceptually possible that gender ideologies influence the practice of physics, even "good" physics. In particular, she argues that gender ideologies can influence "how scientists understand or justify their cognitive goals or [...] values." The question of whether gender ideologies have in fact influenced physicists in this way is an empirical one. Rolin describes two cases in which such influence is claimed, but finds the evidence lacking. There are a great many more cases, however, that have not yet been analyzed this way, and may provide some very fruitful research programs.

Finally, there are a wide variety of studies in the social practice of physics, but they are mainly confined to description rather than prescription. If feminist analyses are to have any real impact, we must go beyond describing the implicit and explicit sexism in physics and decide what changes to make in our pedagogical practices. As Auchincloss (1998: 15) notes, "feminist studies may hold a key to the success of efforts to attract and retain women [...] create gender equitable environments [...] and to reform physics education." Concrete proposals, based on sociological and psychological research, for improving physics education, as well as the testing of these proposals, are wide open areas of research.

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