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(BABY) STEPS TOWARD FEMINIST PHYSICS

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In this exploration of some possible pathways into feminist physics, I take ideas from feminist philosophers of science and feminist science studies scholars about what feminist science should be. I look at the work of feminist scientists in other fields as role models. Using these guidelines, I develop nine categories of projects that are feminist or potentially feminist. I illustrate these categories with examples of contemporary physics research. With this work I hope to guide the steps of feminist physics and encourage other feminist scientists to develop these and other projects.

KEY WORDS: *feminist critique of science, feminist physics, gender and science*

1. INTRODUCTION

Over the past two decades or so, feminist philosophers of science and feminist science studies scholars have produced a rich and complex body of work on the feminist critique of science. For a feminist scientist the natural next step is to ask what feminist science might be. What does a feminist scientist actually *do* when she steps into her lab? Or sits down at her computer to do a calculation? Or walks into her classroom? And how do these practices differ from those of nonfeminists?[1] This is a very different question from that addressed by most feminist critics—what Subramanian calls a project of reconstruction rather than deconstruction:

> *Most of feminist science studies seemed to me to be loosely called a project of deconstruction-that is, taking apart the visible workings of science to highlight the invisible factors that shaped the interconnections between nature and culture, science and society. The project I wished to embark upon was one of reconstruction-to use these insights of deconstruction to rebuild a practice that was scientifically rigorous, but also informed by the rigors of feminist politics and scholarship." (Subramanian, 2001, p. 57)*

How do we begin to define the practice of feminist science? Keller (1983) argued that McClintock's "feeling for the organism" amounted to a more holistic, almost mystic, method of practicing science, though she stops short of calling it feminist. Haraway (1989) describes how Altman used her feminist principles to design methods of observing primate behavior that were recognized by the community as more objective—an irony considering the feminist critique of objectivity.

[1]It is important to note that I am not concerned here with questions of equity—how to interest more women in physics, or how to help the physics community become more diverse. These are important topics, and I discuss them briefly in Sec. 2.7. But, here I am interested in how the *content* of physics might change if some physicists began to view their research through a feminist lens.

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And there are projects that are clearly feminist in their outcomes, for example, King's identification of an allele of the BRCA1 gene that causes some breast cancers (Lee, 2011). Or Colwell's study of *Vibrio cholerae*, and her discovery that eight layers of sari cloth would reduce the population of *V. cholerae* in drinking water, and would reduce the incidence of cholera in Bangladesh by half (Colwell, 2008).

Roy, like Subramanian, is formally trained in both science and feminism. She has written effectively of her anxieties about carrying on her doctoral research in reproductive neuroendocrinology as a feminist. She believed her outcome would be beneficial for women's health, but worried about "how to apply feminist analysis to the 'technical core' of science" (Roy, 2008). By studying several different philosophies of science, she develops a feminist methodology for science.

These examples are useful and interesting, but they all deal with life sciences. In the physical sciences, where the objects of inquiry are not gendered, where women are scarce, and where feminist voices are almost nonexistent, we have to look harder to find a feminist path. In her thoughtful book, *Has Feminism Changed Science?*, Schiebinger tacitly acknowledged this difficulty when she left physics and math until the last chapter, and then talked mostly about equity. She concluded, "In physics and math, we wait for people with the proper training and opportunity to explore the impact of gender on those bodies of knowledge" (Schiebinger, 1999, p. 181).

Physicist Bug, building on Schiebinger's work in a paper titled "Has Feminism Changed Physics?" (2003), finds interest in the physics community for bringing more women and under-represented minorities into physics, and in incorporating (usually unacknowledged) feminist principles into physics pedagogy. But she finds no interest in, even hostility to, the idea that the content or methods of physics might be changed by feminism. She points to the poor match between the principles of feminist science and those practiced by physicists, and concludes that feminism has had essentially no impact on the content of physics. Nevertheless, she suggests that "feminism and women studies have insights to offer physics-if physicists would only permit it!" (Bug, 2003, p. 881).

In this paper I use my knowledge of physics and of the feminist critique of science[2] to explore the possibilities for feminist physics. I use what might be called a "bottom-up" approach to physics, in which the questions grow out of the context rather than the content. In most fields of conventional physics, like high-energy or condensed matter physics, we start with a set of assumptions, an accepted body of knowledge, and a list of important questions open to investigation. A student enters the field by taking graduate courses, finding a mentor to work with, and beginning to work on one of the outstanding questions. Given this model, it is hard to see what feminist physics might be. What would be the subject matter? What would the graduate courses consist of? Who would teach them? What research projects would grow from these courses?

But there is another set of subfields of physics, exemplified by biophysics or environmental physics. Here we begin, not with a set of assumptions and theories and experimental methods, but with a set of problems tied together by their context. A student begins in such an area with a problem, perhaps improved medical imaging or higher efficiency solar panels. Then she learns the physics relevant to this problem, perhaps optics for medical imaging, or condensed matter physics for solar panels.

If we take this approach, we can look for projects that grow out of questions suggested by

[2]A review of the critique of science, from feminist and other points of view, over the past twenty or so years is beyond the scope of this paper. My references are an idiosyncratic list of the work that has been important to me in developing my ideas about the potential for feminist physics, and should not be taken as comprehensive.

feminist critics of science. Or we can look at the work of feminist scientists in other fields as role models. Or we can look for work on the borders of physics that might change the community of physicists, or might change the way that physicists think about our science. Then a number of categories of research projects in physics present themselves as partially, or potentially, feminist. Using my knowledge of feminist science studies, along with my understanding of physics, I develop a number of these categories, along with specific examples of current physics research projects. This list of categories is not comprehensive—there are certainly other lines of inquiry that might be followed. Nor is it coherent—I draw on different strains of feminist theory and find my examples in different subfields of physics. There are undoubtedly some who would like to rearrange and redefine these categories.[3]

The very undeveloped nature of feminist physics means that these really are the staggering steps of a baby learning to walk. If others find ideas in these categories and examples that they can develop, then these small uneven steps can grow into productive paths.

2. CATEGORIES OF FEMINIST PHYSICS PROJECTS

2.1 Projects that Problematize the Knowing Subject/Object of Inquiry Split

> *The subject of knowledge-the individual and the historically located social community whose unexamined beliefs its members are likely to hold "unknowingly," so to speak-must be considered as part of the object of knowledge from the perspective of the scientific method. (Harding, 2004, p. 136)*

> *Situated knowledges require that the object of knowledge be pictured as an actor and agent, not a screen or a ground or a resource, and never finally as slave to the master that closes off the dialectic in his unique agency and authorship of "objective knowledge." (Haraway, 2004, p. 95)*

As the two quotations above demonstrate, feminist standpoint theory demands that the all-knowing invisible subject (what Haraway calls the "view from nowhere") and the passive object of knowledge be treated on a more equal plane—that the subject be considered to be part of the process of knowledge acquisition, and that the object be considered an active agent in the process of observation.

The development of quantum mechanics at the beginning of the twentieth century brought the nature of the subject/object split to the attention of physicists. In order to the test the predictions of any scientific theory, we need to make a measurement, which is clearly an interaction between the subject making the measurement and the object being measured.

To take a simple example, to see an object we must shine light on it. Light, by its wave nature, imposes limits on how accurately we can see (i.e., observe the position of) an object; no wave can localize an object on a scale smaller than its wavelength. In addition, light waves carry momentum that deflects the object and limits how accurately we can predict its future behavior. In prequantum physics, physicists thought that we could reduce the effects of both these interac-

[3]Some readers might object (in fact one reviewer did object) that I have not provided a comprehensive definition of what feminist physics is, or might be. In keeping with the "bottom-up" approach of this paper, I am trying to define feminist physics by suggesting various ways in which specific projects might be considered feminist. These categories, taken together, constitute my definition (or at least a start on a definition) of what feminist physics might be.

tions; we could localize the object more accurately by using light with a shorter wavelength. And, we could reduce the effect of the interaction by using dimmer light that carries less momentum. This means that we could measure position as accurately as we liked, with as small a disturbance to the object as we liked. In this circumstance, it makes sense to assume that we could clearly separate the observer and the observed object, and claim that the object does the same thing whether we are looking or not.

This assumption breaks down in quantum mechanics, where we discover that light does not interact with matter as a wave but as a photon, a particle that carries momentum inversely proportional to its wavelength. We can indeed localize an object more and more carefully, using shorter wavelength photons. But as we do so, the momentum of the photon increases, causing greater and greater disturbance to the object. So our assumption that an object will do the same thing whether we are looking or not is clearly false.

Quantum theory of measurement was of great interest for early theorists, and the subject of an important debate between Bohr and Einstein.[4] It was Bohr who most fully explored the implications of quantum measurement, not just for the subatomic world but for our interactions with the world in general. He argued that properties like position and momentum do not exist in themselves, but are created by the interaction of measurement.

But the issues raised were so disturbing, and quantum mechanics was so successful at solving problems that most physicists adopted a "shut up and calculate" approach, defining the problems raised by measurement as "philosophical" (i.e., not our problem). A few theorists, most notably Bohm and Bell, continued to explore the epistemological issues raised by quantum measurement.[5] But the only physicist to take Bohr's philosophical legacy seriously, and to develop it in explicitly feminist directions, is Barad. Drawing on a close reading of Bohr's philosophy-physics (she says he does not distinguish between the two practices), her own training as a theoretical physicist, and contemporary feminist science studies, she finds a middle ground between the naïve and often apolitical realism of many physicists, and the often antirealist social constructivism of many science scholars. She constructs agential realism, which she describes in a 2007 book with the evocative title *Meeting the Universe Halfway* (Barad, 2007).

In contrast to Bohr, who focuses on the interaction between the observed object and the measuring apparatus, Barad expands this view of measurement to include as well the human observer. The object under observation, the measuring apparatus, and the person making the measurement are entangled together in a "phenomenon"—a relationship that is prior to any of its parts.[6]

> *According to Bohr, the central lesson of quantum mechanics is that we are part of the nature we seek to understand. (Barad, 2007, p. 247)*

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[4]This brief discussion does not do justice to the difficulties surrounding the quantum theory of measurement. The best nontechnical discussion is by Feynmann (1967), which I highly recommend to those interested in pursuing the topic. A very complete collection of reprints, including the original papers by Bohr and Einstein, is to be found in Wheeler and Zurek (1983).

[5]It is possible that the relatively new field of quantum information, which takes quantum properties as a resource rather than a limitation, may lead other physicists to reconsideration of the epistemological implications of quantum mechanics.

[6]I am concerned that I appear to be giving short shrift to the only feminist physicist doing explicitly feminist physics. This brief discussion cannot possibly do justice to Barad's complex and elegant theory. In particular, my discussion is limited to the impact of agential realism on quantum measurement; Barad presents an epistemological, ontological, and ethical description of the human and nonhuman worlds. For a complete discussion see Barad (2007).

Apparatuses are not static laboratory setups but a dynamic set of open-ended practices, iteratively refined and reconfigured. (Barad, 2007, p. 167)

Experimental physicists are not naïve observers passively recording what "nature" tells them. They are highly trained, very clever physicists who design and build complex instruments, carefully calibrate them, track down and eliminate systematic errors, and perform sophisticated data analysis. Each of these activities involves active choices by the physicist, and each of these choices helps to determine the phenomenon that ultimately decides the result of the measurement. New and different experimental results are often the result of new and different choices by the experimenter.

Sometimes the gender, race, class, and other demographic characteristics of the experimenter can be clearly seen to be a factor in her choices. Rubin, for example, chose to study the outer reaches of galaxies because, as the mother of small children, "I didn't want to compete with what other people were doing." (Rubin, 2004). She discovered that the outer reaches of galaxies contain much more mass than expected; this is the most direct evidence for the existence of Dark Matter (Rubin, 1997). See Sec. 2.9 for further discussion of Dark Matter in contemporary cosmology.

2.2 Projects that Reconceptualize Physics in Less Reductionist Directions

Science has been about a search for translation, convertibility, mobility of meanings, and universality-which I call reductionism, when one language (guess whose) must be enforced as the standard for all translations and conversions. What money does in the exchange orders of capitalism, reductionism does in the powerful mental orders of global sciences: there is finally only one equation. (Haraway, 2004, p. 85)

The eventual goal of science is to provide a single theory that describes the whole universe. (Hawking, 1988, p. 10)

The enforced universality described by Haraway and Hawking is one aspect of science most criticized by feminists. Here physicists are the most vulnerable—our science deals with the smallest objects known, with matter at its most fundamental level, and we gain great status among our fellow scientists from that position.

…if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. (Anderson, 1972, p. 393)

Anderson usefully distinguishes between a hyper-reductionist hypothesis that he calls "constructivist" and a somewhat softer version that he calls "reductionist." The reductionist hypothesis states that everything does obey the same fundamental laws, and is probably believed by most practicing scientists. All objects, whatever their complexity, obey the laws of physics—a living organism, for example, falls according to Newton's laws when dropped off a cliff. The constructivist hypothesis suggests that we could (at least in principle) start with the laws of physics and construct the universe, including living organisms and human society. It is rare for a scientist to explicitly claim the constructivist hypothesis, and there is no evidence that it is correct. Nevertheless, physicists like Hawking (1988) do seem to tacitly assume that if the problems of quarks or strings are solved, all other scientific problems will be trivial and uninteresting. But even in physics there are counter trends, and physicists who are working to make less reductionist connections between different levels of science.

An example may be helpful here. About a century of work by atomic physicists has taught us a great deal about atoms, ions, and small molecules. By devising clever calculational tools and ingenious experimental methods, atomic physicists have measured and calculated the electronic structure and energy levels of most individual atoms, and how they interact by twos and threes.

A constructivist scientist might assume that this highly detailed and accurate information about the properties of individual atoms and molecules would be applicable to understanding atoms and molecules in bulk—the properties of gases, liquids, and solids. Yet despite their differences at the atomic level, all gases are very much alike (as those of you who remember the ideal gas law from introductory chemistry can attest). A highly polar molecule like water vapor forms a gas very similar to a very non-interactive atom like helium (at least when the conditions of the gas are far from the condensation point). The few parameters that we need to understand the behavior of gases are actually quite hard to calculate from atomic properties—it is easier and more accurate to measure them, and that is what, in practice, people do. The properties of solids, liquids, and gases are collective properties that do not depend significantly on the properties of the individual particles that make them up. So, all the work done by atomic physicists is not particularly useful for a better understanding of gases or, indeed, any large system of particles.

Even more amazing, collections of atoms or molecules have properties that are unique to the collective states. Properties like the rigidity of solids or the viscosity of liquids have no analog in the atoms themselves. They are collective properties (Anderson calls them emergent properties) that appear gradually as the number of atoms in the system gets large (large in the thermodynamic sense means *very* large—10^{20} or so atoms).

If we think of this example in Anderson's terms, we see that it is reductionist but not constructionist. The individual atoms and molecules in a solid do obey the rules of atomic structure. But it is not possible to use these rules to create a solid or deduce its collective properties—we cannot *construct* the solid from the rules concerning the individual atoms.[7] A carbon atom has the same number of protons, electrons, and neutrons, and (more or less) the same structure in a diamond crystal or in a protein, as when it is alone. But we cannot deduce the properties of diamonds or proteins from our understanding of carbon atoms.

A group of physicists including quantum field theorists and statistical mechanicians has been working to understand more rigorously the relationship between one layer and another. In the process they have solved some of the most important problems of mid-twentieth-century physics. They have put quantum field theory on a sound mathematical basis by learning how to eliminate calculations that run away to infinity. And, they have developed new methods to deal with phase transitions like the boiling of a liquid.[8] Perhaps even more important, each group learned from the work of the other, confounding the reductionist idea that knowledge only moves up from lower layers.

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[7]In this particular case, the new and rapidly developing field of nanoscience is studying the properties of collections of atoms that lie between the atomic and statistical layers. In some experiments, physicists are studying the development of bulk properties like electrical conductivity as the number of atoms increases. However, the possibility that some of the connections between layers can be filled in does not mean that all science is constructivist. I am grateful to Kristine Lang for pointing this out.

[8]There is a large and complex literature describing these phenomena. Two useful semitechnical references are Wilson (1979) and Schweber (1993). An interesting nontechnical description is found in chapter 4 of Laughlin (2005).

This work has very profound effects on how physicists and other scientists think (or should think) about science. If the laws of atomic behavior do not affect in significant ways the laws of collective atomic behavior, then there is no most fundamental bottom layer that is more important than any other layer. Particle physics is no more profound than ecology; each has its own concepts and laws, and each is equally important.

> *Rather than a Theory of Everything, we appear to face a hierarchy of Theories of Things, each emerging from its parent and evolving into its children as the energy scale is lowered. (Laughlin and Pines, 2000, p. 30)*

I do not mean to argue here that it is always wrong, bad science, or nonfeminist for scientists to apply reductionist methods to solve problems. Reductionism has given us powerful methods that are very successful in fields like particle physics or molecular biology. King, after all, used reductionist methods to complete the feminist project of identifying breast cancer genes (Lee, 2011). I am arguing, rather, that these enormous successes have led some contemporary physicists to overemphasize reductionist and even constructivist thinking. A feminist physicist need not abandon reductionism, but she should remember that taking things apart is not always the best way to understand them, and that they need to be put back together again afterward.

2.3 Problems that Use Local Solutions to Solve Local Problems and Achieve Global Understanding

> *Nonhuman nature, therefore, is not passive, but an active complex that participates in change over time and responds to human-induced change. Nature is a whole of which humans are only one part. We interact with plants, animals, and soils, in ways that sustain or deplete local habitats. Through science and technology, we have great power to alter the world in short periods of time. The relation between human beings and the nonhuman world is thus reciprocal. Humans adapt to nature's environmental conditions; but when humans alter their surroundings, nature responds through ecological changes. (Merchant, 1989, p. 8)*

> *Living cultures grow from the earth, emerging from particular places and spaces while simultaneously connecting all humanity in a planetary consciousness of being members of our earth family. (Shiva, 2005, p. 7)*

In traditional academic institutions, the natural and the social are rigidly separated; the natural world is studied by natural scientists, and human culture by social scientists and humanists. Even ecologists, who are interested in interacting systems, usually confine their attention to the interactions of "wild" ecosystems, untouched by human cultures.

The growth of environmental science programs that study the interaction between human beings and the natural world, often including both natural and social science methods, is starting to break down this separation. Ecofeminists like Merchant have helped us understand how our interactions with the natural world structure are structured by our cultural history. Shiva asks us to view environmental issues from the perspective of Third World women, a good example of Harding's advice to start from marginalized women's lives. Proper environmental solutions, according to Shiva, take account of local cultures and local environments. She envisions a network of local cultures connected together into a global network.

Physicists are much better at global than local thinking. Our methods emphasize universal principles like conservation of energy and momentum, and finding similarities between problems that are superficially very different (like quantum field theory and phase transitions, as in the second category). We can learn from other areas of science where local particularities are important.

Uttal is an atmospheric physicist working for National Oceanic and Atmospheric Administration who studies polar regions, which she calls the "climate bulldozer," driving global warming in a positive feedback loop that accelerates the cycle. Polar regions are poorly understood and difficult to study because of harsh conditions, extreme seasonal variability, and a lack (at least in the North) of land-based observation platforms. But because the temperature and salinity of polar water drive global circulation, polar regions are critical to understanding global climate.

With an interdisciplinary team of polar scientists, Uttal carried out a project called SHEBA (Surface Heat Budget of the Arctic Ocean). An icebreaker ship was frozen into the Arctic pack ice and left to drift for a full year while the team studied the atmosphere, ocean, sea ice, and snow cover. They fielded dozens of instruments, the goal of which was to measure the transfer of energy and matter into, through, and out of a column reaching from the atmosphere through the snow and ice and into the ocean. Figure 1 shows a sketch of the project, and some of the measurements made. The project was designed to collect information that can be fed back into the Global Climate Models that use a grid of such columns to predict future changes in the earth's climate (Uttal *et al*., 2002).

Environmental problems like global warming show that ecofeminists are right to emphasize the interaction between natural and human history, and SHEBA demonstrates an ecofeminist approach to understanding and solving these problems. An interdisciplinary group of scientists applied universal principles like conservation of mass, energy, and momentum to understand the complexities of a particular place. The rich understanding of this place gained by SHEBA is recycled back into computer models to lead us to a better understanding of the global problem of climate change.

2.4. Problems that Apply Physics to the Solution of Human Problems

> *On the one side stand "pure nature" and the "pure science" that can tell the one true story of pure nature's order. On the other side stand various "impure" objects of knowledge and the disciplines or methods of knowledge seeking that try to understand them…Sciences that study objects of mixed natural and social knowledge-such as health sciences, agricultural and environmental sciences are far more the object of [Third World] feminist interests. Such sciences must themselves combine theoretical frameworks and skills found both in the natural and social sciences. Should we call them "mestiza" sciences, in reference to Anzaldua's eloquent elaboration of the characteristics of people living on the borderland? (Harding, 1998, p. 87 and note 19, p. 209)*

As Harding aptly describes, physicists and most other scientists privilege pure over applied science—applied, that is, to problems generated by people's lives. For most of the twentieth century, the fundamental problems of physics, the solutions to which won the Nobel Prize, were questions about the material universe at the smallest accessible scale. This work originally had very important applications in chemistry, molecular biology, and materials science. But as the century progressed, the fundamental questions moved to smaller distances and higher energies and became more remote from human life.

Waymouth is a recently retired atomic and molecular physicist who spent his entire career

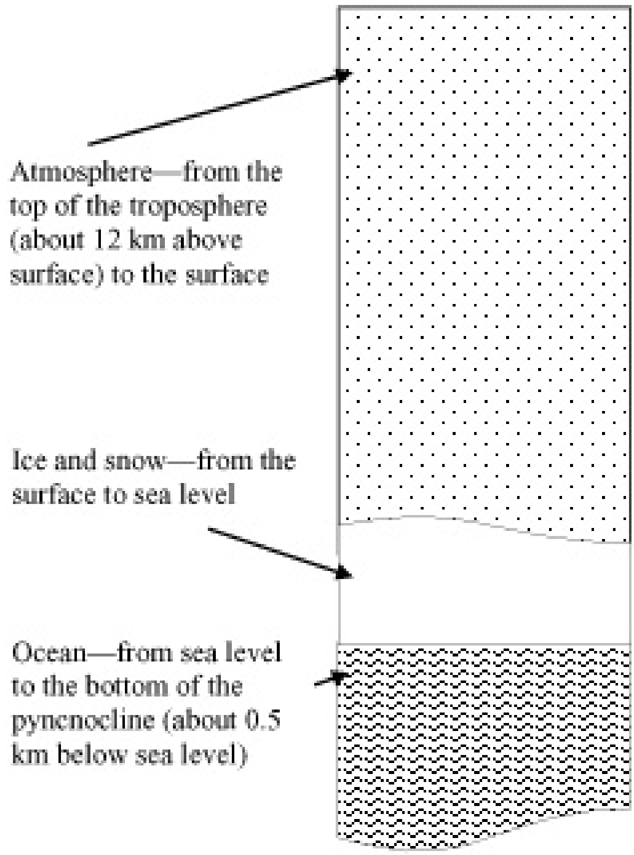

FIG. 1: The approach of the SHEBA project was to consider a column of material from the top of the troposphere (the lowest level of the atmosphere) down through the snow and ice on the surface and into the ocean, ending at the top of the pyncnocline (the bottom of the uppermost level of the ocean). This approach was chosen to match the format of computerized Global Climate Models, so that the information gained could be used to improve modeling of polar regions. Material and radiation fluxes were measured, both horizontally and vertically, through all the layers of the column. For the atmosphere: precipitation, winds, temperature, humidity, clouds, and radiation. For ice and snow: depth and stratigraphy, temperature, thickness, and reflectivity. For the ocean: temperature, salinity, diffusivity, heat fluxes, and currents.

working on lighting technology for Sylvania. In 2000 he received the Will Allis Prize of the American Physical Society, and in his acceptance speech said:

> *I spent my entire working life using physics to grub for paydirt in an industrial setting…In such a setting, any project that yielded only meeting presentations or publications in refereed journals had to be considered essentially a failure…Academic scientists can point to their publications as the validation of their life's work. I can see mine whenever I go to the mall and look up at the lights. (Waymouth, 2001)*

Waymouth describes the development of high-intensity fluorescent lighting—a major success of his early career. Creating and solving a model of the plasma discharge was a difficult problem in those precomputer days. The solution led him to propose some changes in the makeup of the gases inside the tube. This was, Waymouth says, the end of the physics. But he still had to work with electrical engineers to design and fabricate new electrodes, figure out how to put them into mass production with the line engineers, think about the economics of the process, and persuade managers to keep funding his project until he could demonstrate that his new lights could be mass produced reliably and economically. This very interdisciplinary work has some of the characteristics of the "mestiza" sciences described by Harding above—it involves economics and other social sciences as much as physics.

Standpoint epistemologists like Harding (2004) argue that feminist science should begin by taking everyday life as problematic, and by starting from marginalized lives. The working class women who are clerks in shopping malls are grateful (or would be if they knew) to Waymouth for providing bright, efficient lighting for their workplace. Some physicists and engineers are working on the design of technology like white light-emitting diodes or solar-powered water purifiers intended to make the lives of poor Third World women safer and less difficult.

2.5 Problems that Set Contemporary Physics Research in Its Social and Political Context

> *Cultural agendas and assumptions are part of the background assumptions and auxiliary hypotheses that philosophers have identified. If the goal is to make available for critical scrutiny* all *the evidence marshaled for or against a scientific hypothesis, then this evidence too requires critical examination within scientific research processes. (Harding, 1991, p. 149; emphasis hers)*

Traditional scientists and philosophers of science separate the process of scientific discovery into the "context of discovery" and the "context of justification" (Kuhn, 1970). Careful methodological controls are applied only to the latter; the former is described as outside the logic of the scientific method. Harding (1991) objects to this division; she says that it lets scientists off the hook by allowing us to ignore the context out of which our work grows, and into which applications of our work will fit. She substitutes the principle of strong objectivity, which suggests that to obtain the most reliable and authentic information about the natural world, scientists should subject the questions of how their research agenda arise, and to what uses their results are put, to the same rigorous investigation that we give to the path from questions to answers. This, she argues, will allow science to serve politically liberatory goals.

Lane, after a distinguished career in theoretical atomic and molecular physics, devotes much of his time to being what he calls a civic scientist, using his expertise in physics to influence policy decisions. He directed the National Science Foundation (1993–1998) and served as Director of the White House Office of Science and Technology Policy (1998–2001). Currently he is University Professor of Physics at Rice University, and Senior Fellow for Science and Technology at James Baker Institute. His model for a civic scientist is Franklin (Lane, 2003). Although his place in American history is dominated by his political work, Franklin also made significant contributions to the early development of the theory of electricity. His *Experiments and Observations on Electricity* (1749) was well-known and respected in Europe, and his scientific eminence probably made him a more effective ambassador to France. Lane urges other scientists to play a larger role in politics, and has developed "Franklin's List" (shown in Table 1) of steps Franklin

TABLE 1: Franklin's List

Steps that (according to Lane) Franklin would urge scientists to take to apply their scientific expertise and authority to social concerns:

1. Encourage scientists to run for Congress and other public office, and establish a bipartisan science caucus.
2. Organize a series of science seminars for policy makers.
3. Work to increase the nation's overall science literacy.
4. Assemble a science literacy handbook that includes dos and don'ts for scientists.
5. Educate students about science and civic responsibility. Scientists could volunteer to help in settings from preschool child development centers through the entire educational system.
6. Gather the best scientists and science writers to reform and rewrite science textbooks and curricula.
7. Make better educational use of television, computers, and computer games.

would urge scientists to take to apply their scientific expertise and authority to social concerns.

Other scientists place their expertise and authority at the disposal of grassroots or disempowered groups. Redsteer (she is not a physicist, but she is too good an example to pass up) is a member of the Crow (Absalooka) Nation and a USGS geologist who studies the effects of drought in the Navajo Nation. Her interdisciplinary project involves geomorphology, hydrology, botany, and anthropology. She spends a significant amount of her time at Chapter House meetings explaining her project and her results to the local people. Her graduate students who take the time to talk to local people and treat them with respect do better work than those who try to distance themselves in order to be "objective." This respectful attitude is more important than ethnicity; one of her most successful students was an Anglo from Wisconsin (Redsteer, 2005). This seems to me to be a very visible example of what Harding means by strong objectivity; by working with the Navajo community and learning from them, Redsteer and her students obtain a more complete picture of the effects of drought, and do *better* science by considering and respecting the cultural setting of their work.

Redsteer also works with Native students in an effort to interest more young Natives in science, believing that tribes would benefit from scientific authority of their own. Here again she is taking pains to consider the uses to which her science is put, so that it will serve the needs of the disempowered.

Many scientists, including physicists, argue that our responsibility is only to our narrowly defined science—we are required to be meticulous only about our means. To take political positions as scientists reduces our objectivity. For scientists like Lane and Redsteer to argue that we have a responsibility *as scientists* to consider our ends as well, moves science in very feminist directions.

2.6 Projects that Reintegrate Physics into Its Cultural and Environmental Setting

This next group of categories is somewhat different; most projects are not "real physics," in the sense of being publishable in *Physical Review* or some other physics research journal. Some physicists do this work, and so do people in history of science, education, and social science. I include them as feminist physics projects because they broaden our view of who physicists are and what physicists do. This broader view makes the path toward feminist physics more clear.

> *In other words, we can think of strong objectivity as extending the notion of scientific research to include systematic examination of such powerful background beliefs. (Harding, 1991, p. 149)*

Another application of strong objectivity involves setting scientific projects of the past into their social and political contexts. One important group of feminist physics projects is the restoration of Western women physicists and physicists of color to their proper place in history. These people had been so thoroughly erased from our history that in 1986, Harding wrote that the path to feminist science cannot be the same as in other fields because “there are few women worthies to restore to the science hall of fame.” (Harding, 1986, p. 31). That so prominent and thoughtful a philosopher of science could say this testifies to the effectiveness with which women and minority scientists have been erased from our history. And the explosion of work[9] since then shows how wrong we all were; no matter how high the barriers placed before them, some strong and determined women and men of color have *always* found ways to practice science. The substantial body of work that has been done in recent years to resurrect and restore the work of women physicists and physicists of color to their proper place in history has many benefits. It corrects the history of our science and makes it clear that physics is less white and less male than conventional history might imply. It creates role models for diverse students and shows them that they, too, can have a place in physics. And it’s only fair to restore the reputations of people who have been systematically erased from the history of science.

A second group of projects in this category is the study of the physics of other cultures. Harding (1998) has carefully documented the Eurocentrism of much of the work on the history of science, and the self-serving quality of most definitions that say that only European culture developed “real” science. We need to study the physics of other cultures for two important reasons. First, we must set the record straight. Other cultures should receive the credit that is due their inventiveness and efforts to understand the physical world. And second, “mining” [to use Goonatilake’s (1998) evocative term][10] the knowledge of other cultures will provide additional resources to help contemporary global science solve the problems of our time.

Needham’s exhaustive study of Chinese science (1954) is very much in the Eurocentric tradition, written to explain why the Chinese never developed modern science. Nevertheless, he makes a number of important points about Chinese physics. For example, he argues that the Chinese view of an organic world governed by natural cycles leads more easily to a wave picture of physics that complements the particle picture prevalent in much of European physics. It was natural then for the Chinese to develop optics and acoustics. The wave theory of light, for example, was invented in China long before European physicists developed it, and they may have learned from Chinese examples.

We have much to learn about the physics of other cultures. There is a good deal of work on ethnoscience in fields such as mathematics and botany, but little on physics [see Selin (1997) for an overview of the science of non-Western cultures]. There is much to be learned if physicists study how other cultures conceptualize physical reality. What is the world made of? How are

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[9]There is a wealth of examples documenting the work of women scientists, including histories of early women scientists (Alic, 1986) and biographies of famous women physicists like Meitner (Sime, 1996). No list would be complete without Rossiter’s monumental history of women scientists in America (Rossiter, 1982, 1995).

[10]The term “mining,” with its history of cultural appropriation and environmental damage, is only too appropriate. Great care must be taken with these projects to avoid further exploitation.

matter, energy, and life categorized? How do people think about gravity? How do they think about material cycles like energy, water, air? How do they use materials to construct their physical environment? How do they construct and use technology?

Further work on the physics of other cultures will give us a more complete view of how the human race views physical reality. And, it may give us new ideas, new metaphors, and new approaches to understand and solve the complex problems facing us.

2.7 Projects that Increase the Diversity of the Physics Community

Nelson (1993) has argued that it is the scientific community as a whole, not individual scientists, who are the agents of scientific knowledge.

> *In suggesting that it is communities that construct and acquire knowledge, I do not mean (or "merely" mean) that what comes to be recognized or "certified" as knowledge is the result of collaborations between, consensus achieved by, political struggles engaged in, negotiations undertaken among, or other activities engaged in by individuals who, as individuals, know in some logical or empirically "prior" sense… My arguments suggest that the collaborators, the consensus achievers, and, in more general terms, the agents who generate knowledge are communities and subcommunities, not individuals. (Nelson, 1993; p. 124, emphasis hers)*

A brief look at the physics community confirms Nelson's argument. No one becomes a physicist without years of instruction in what constitutes a physical theory, how one performs a calculation or measurement, and what we regard as evidence. Almost no one practices physics without obtaining support from a network of funding agencies staffed by physicists. Almost no one works in isolation; a glance through any physics journal shows how rare single-authored papers are. No one's work become a part of physics until it is reviewed and accepted by the community of peers. In Nelson's sense, it is the community of physicists rather than an individual physicist who is the primary knower.

> *The conception of value-free, impartial, dispassionate research is supposed to direct the identification of all social values and their elimination from the results of research, yet it has been operationalized to identify and eliminate only those social values and interests that differ among the researchers and critics who are regarded by the scientific community as competent to make such judgments. If the community of "qualified" researchers and critics systematically excludes, for example, all African Americans and women of all races and if the larger culture is stratified by race and gender and lacks powerful critiques of this stratification, it is not plausible to imagine that racist and sexist interests and values would be identified within a community of scientists composed entirely of people who benefit-intentionally or not-from institutionalized racism and sexism. (Harding, 2004, pp. 136–137)*

Harding's argument shows that the nature of the physics community is an important determinant of the quality of the knowledge we generate. The physics community is one of the most homogeneous, even in science; most recent statistics show that doctoral level physicists in the US are 87.5% male and 75% white (NSF, 2011, Tables 9-5 and 9-6, respectively). This whiteness and maleness is a limitation, not only for equity and social justice, but for the quality of the science we do. Projects that are designed to increase the diversity of the physics community are therefore feminist projects that will lead to a more value-free, impartial, dispassionate, and feminist physics.

Included in this category are projects that document, especially quantitatively, the subtle bias that persists and pushes all but the most determined women and men of color out of the field. Other projects are designed to interest girls in middle school and high school in science, to make physics departments more female-friendly, and to support women and men of color in physics careers.

Projects like these are often criticized by feminists as liberal feminism, designed to increase the access of women and minorities to physics as usual, without changing the assumptions, content, and methods of a science they find much fault with. I do not disagree with this sentiment, but I do think, to borrow Tuana's phrase (1992), that these liberal projects have a radical future. If we change the makeup of the physics community, if we attract to physics a larger proportion of women and minority students, if we support those few women and students of color who do choose a physics career, we will change the nature of the physics community, the kinds of questions we are asking, and the uses to which our science is put. We have seen other fields change significantly as women entered the field and gained a distinctive voice. Richardson (2008) described how feminist criticism helped define current ideas about the genetics of sex determination. Wylie (1998) describes how the entry of women into archaeology exposed the androcentric underpinnings of the "man the hunter" paradigm of early human history. I believe that this will also happen in physics as our community becomes more diverse.

2.8 Projects that Change the Way Physics Is Practiced and Taught

> *…in order to teach our subjects we must adopt the language and ideas of our fathers-ideas that often exclude us as women or describe us in ways that at times have been oppressive. (Brickhouse ,2001, p. 283)*

Brickhouse points out that including some women and men of color in the scientific community will not effect significant change in science as long as these diverse people are educated to be just like the white men who are already there. A more radical category of projects are those that try to modify the way physics is taught and practiced. Science education has been the subject of much feminist criticism; Rosser (1990, 1997) provides a particularly complete discussion. Brickhouse (2001) analyzes several educational models for their feminist potential. In the past twenty years or so, the physics community has devoted significant effort to modifying the introductory physics course. These efforts are not explicitly feminist, as Rosser points out, but they do draw on feminist pedagogy, and one of the stated goals is to make physics more appealing to a broader range of students.

Equity projects that focus on peer review have a particularly significant effect on the practice of science. As Harding describes above, submitting one's work to the scrutiny of one's peers is crucial to the elimination of bias, so inequities in peer review are particularly threatening to the quality of our science. Peer review is ubiquitous in science, not only in publication, but in the awarding of grants, fellowships, and honors. Recent work has uncovered gender bias in reviewing fellowship applications (Wennerås and Wold, 1997), choosing invited speakers (Brumfiel, 2008), and acceptance of papers (Budden *et al*., 2008).[11] There is little discussion of this in the physics community; a dis-

[11]These studies have generated a significant amount of work, and some controversy. Sandström and Hällsten (2008) reinvestigated the procedures of the Swedish medical research council analyzed by Wennerås and Wold (1997) and found that sexism has disappeared, but nepotism

cussion of peer review in *Physical Review* (Schuhmann, 2008) made no reference to either potential gender (or other) bias or to double-blind reviewing. Physicists in general (based on many personal conversations) have little understanding of unconscious bias, and equate bias with deliberate sexism. It is difficult to discuss these issues, therefore, without offending people.

Another potentially feminist category of projects are those that reorganize research groups along less hierarchical lines. As described in Sec. 2.5, Redsteer's care to explain her research to the communities affected, and her efforts to involve younger members of the community in her work, offer a model of how a feminist science project might be more community based.

Some astronomy projects build collaborations between professional and amateur observers in potentially feminist ways. During the International Geophysical Year, Whipple of the Smithsonian Astrophysical Observatory organized teams of amateur astronomers, including high school students and Girl Scout troops, to track the newly launched artificial satellites in order to calculate their orbits (McCray, 2006). A recent experiment in "open source science" is exploring the possibility that an open team of mathematicians can achieve significant results. The team of mathematicians, ranging from a high school teacher to Fields Medal winners, are sharing ideas over the Web. Several papers on the work of the Polymath Project have been published in mathematics journals (Gowers and Neilson, 2009).

The relatively new phenomenon of Community Based Research offers another model of research organization. Science shops, which originated in the Netherlands in the seventies, are "organisations created as mediators between citizen groups (trade unions, pressure groups, non-profit organisations, social groups, environmentalists, consumers, residents association etc.) and research institutions (universities, independent research facilities)." (Living Knowledge, nd.). They are collaborations between a community group that needs expertise and scientists (both natural and social) who can supply it. Weasel describes how these organizations and the projects they undertake have the potential to reorganize both how science is done, and what science is done. "By including marginalized and 'outsider' participation in all stages of the scientific process, this approach allows for a more thorough reorientation and reconstruction of science, not only by redefining the types and kinds of question that are asked but also by critically evaluating and reformulating research methodologies from a marginalized perspective." (Weasel, 2001, p. 310)

A still more radical step along this path is what is being called the "democratization" of science, where groups of nonscientific stakeholders play a role in the process of science. We have important role models in medicine where breast cancer and AIDS activists have helped to redefine research into and treatment of these diseases. Work on sustainability, global warming, and other environmental issues might also follow along these lines, and include physicists in interdisciplinary groups. Bäckstrand (2003) has discussed some of the advantages and pitfalls of this process.

2.9 Projects that Increase Our Respect and Awe for the Natural World

> *To disclose this ambiguity, however, it is necessary to renounce any pretension to impose upon nature our own preconceived notion of what "elements of reality" ought*

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remains. The work of Budden *et al*. (2008) has been disputed by several authors. Budden and her co-workers continue to study the issue and to suggest that double-blind reviewing may be helpful.

to be, and humbly take guidance, as Bohr exhorts us to do, in what we can learn from nature herself. (Rosenfeld, 1967, p. 129)

Now my own suspicion is that the Universe is not only queerer than we suppose, but queerer than we can suppose. (Haldane, 1927, p. 286)

Where advocates of difference within science critically depart from and effectively counter that tendency in post-modernism towards an indefinite proliferation of difference is in their reminder of the constraints imposed by the recalcitrance of nature-their reminder that, despite its ultimate unrepresentability, nature does exist. (Keller,1989, p. 43)

My feminist training has taught me that science is a socially constructed artifact of human culture. My scientific training has taught me that science is an empirically based and theoretically constructed description of the natural world. It is important to understand both sides of this picture, to see that physics is a socially constructed project that is strongly constrained (though not determined) by the natural world.

Feminists are certainly correct to criticize contemporary science as oppressive and aligned with the rich and powerful, and for contributing to the destruction of the natural world. This is an important part of the legacy of science in the contemporary world. But, as the quotes above attest, many scientists are motivated by a deep love of the natural world, and a humble respect for its complexity. If we will listen, science can teach us humility for our ignorance and respect for the Universe we study.

Astronomy offers a wealth of examples of our ignorance in the face of a complex Universe. One particularly telling example is gleaned from a brief study of contemporary cosmology (Carroll, 2004). Beginning with the discovery in 1965 of the cosmic microwave background, our understanding of cosmology exploded because it was now possible to test predictions in a far more quantitative way. In 1998 two groups studying the spectrum of supernovae in distant galaxies independently discovered that the expansion of the Universe is accelerating(!) The only known force operating at cosmological distances is the attractive force of gravity, which would slow the expansion down. To explain this contradiction, cosmologists have invented a mysterious substance known as Dark Energy, and that is pretty much all anyone knows about it. Current models suggest that the mysterious Dark Matter discovered by Rubin comprises twenty-two percent of the Universe, the even more mysterious Dark Energy is seventy-four percent, and ordinary matter is four percent. So, an important effect of our increasingly quantitative understanding of cosmology is that we now do not know what approximately ninety-six percent of the Universe is made of.

Feminist critics argue that in order to understand the natural world, we must place our scientific theories in their social and cultural context. I am suggesting here that the converse is also true—that we cannot solve feminist and other social justice problems without considering the natural and environmental setting of the society and culture. The rapidly evolving environmental crisis makes it clear that starting from women's lives will involve a deeper understanding of the environmental setting of those lives, a respect for the natural world, and an attitude of humility that acknowledges our ignorance.

Finally, an important part of practicing feminist physics is to claim that one's feminist values are part of one's scientific practice. I am well aware of the many dangers of doing this. The risks of being marginalized and discounted and criticized for "mixing science and politics" are real for physicists, and particularly so for younger women and men of color. To do so, however, gives courage to our colleagues and perhaps will make such a declaration less dangerous in the future.

3. CONCLUSIONS

In taking these baby steps toward feminist physics, I have drawn on different strains of feminist epistemology for my categories, and from different subfields of physics for my examples. Readers may find much to disagree with here. Some may argue with my categories, which are neither comprehensive nor coherent, and wish to rearrange them. Some may be troubled by the fact that many, perhaps most, of the physicists I describe would not consider themselves to be feminist, or to be doing feminist physics. Some may argue that I fall between two stools, that some of the examples are physics but not feminist, and others are feminist but not physics.

I welcome all these arguments, which will help define what feminist physics might become. And I hope that feminist physicists will build on this preliminary work, and elaborate my categories or develop new ones, or find other examples. What I most hope is that young feminist physicists will see these examples and be inspired to work on these or other projects. If these projects are seen through an explicitly feminist lens, they will develop in new and interesting directions, and we will have something we can truly call feminist physics.

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