Is Realism Viable in the Midst of Physics and Philosophy?

Phillip Broussard
Physics Department
Covenant College
Five-Year Tenure Paper

He is before all things, and in him all things hold together. (Colossians 1:18)

"Realism is dead." (Aurthur Fine)

1 Introduction

Theories about our world abound in the public square as science makes new discoveries and pronouncements on the nature of reality. Discussions about black holes, string theory, and dark energy have become part of the public discourse. However, this raises an interesting question. When a scientific theory makes successful predictions, how does one view the theory's connection to reality, especially if the theory uses non-observables, objects that are at present incapable of being observed? Two possible extremes of how to view the theory would be scientific realism and antirealism (referred to here simply as realism and antirealism). A historical example of these views is clearly seen in the study of gases, undertaken in the late 19th century. The kinetic theory of matter assumed that gases are made of atoms, which acted like miniature billiard balls, moving in three dimensions and produced the observable behavior of gases, such as pressure. The success of this theory in explaining the properties of gases raised an interesting question: Given the success of the theory, how do you view the existence of these unobservable atoms that are postulated? The realist, in this case exemplified by Ludwig Boltzmann, would say that if the theory is more and more successful in its predictions, we can have greater and greater confidence in the reality of the atoms, even though at his time there was no conceivable way of observing them directly. The antirealist, here represented by Ernst Mach, would say that the increasing ability of the theory to make successful predictions in no way proves the existence of objects that cannot be observed. Mach is famous for standing up in a conference in 1897 and announcing he didn't believe in atoms.(Lindley, p. xi) In this case, the stakes between the two views were quite high, for eventually Boltzmann committed suicide, in despair that his realist views were not being taken seriously. The debate between these two individuals, discussed by David Lindley in his work *Boltzmann's Atom*, shows the tension between realist and antirealist views of science.

In my classes, this struggle between realist and antirealist views of science continues in the minds of my students. Previously, in my three-year paper, I discussed how some of my students view certain areas of science through a fictionalist perspective. Fictionalism, as stated in my earlier paper, is the claim " that although the theory and data may imply a certain result, it only appears that way to our observation and the actual truth is quite different."(Broussard, p. 8) Some students' responses clearly show this view, as shown below:

> However, I believe that God created everything with the appearance of age. The universe was created in the middle, jumpstarted to a particular point, in order to compliment creation on earth. God did create a set of laws to govern what he made but it appears that these laws can only explain how the universe works from 8000 B.C. on.
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> The Earth looks much older than 10,000 years. Why is this?... The answer to the appearance of an old earth has to do with the flood narrative in Genesis 6 ... When the flood subsided, the earth emerged looking much older than it actually was.

I discussed in my previous paper that fictionalism is an extension of antirealism, and argued that it was not a faithful way to look at the results of science. I argued that fictionalism is a hindrance to my students' calling to be good stewards of God's creation, as it tends to shut down any further desire to inquire about God's world and inhibits future study of science. Instead I encouraged a realist view of the sciences, arguing it was the most effective way to carry out science as a Christian. I also clearly laid out the reasons why we must engage in science as followers in Christ: In order to glorify God and to better carry out our stewardship responsibilities.(Broussard, pp. 1-3) As Mary B. Hesse states "...science is given to men that they may glorify God through His works and that they may use it for man's good."(Hesse, p. 27)

My approach to this continued struggle between realism and antirealism has been two-fold. First, I have introduced the realism/antirealism discussion into all the core laboratory science courses that I teach, as well as bringing the issues up in my advanced physics classes. I have found that these issues are of more interest to my physics students than to my students in core science classes. Second, I have read more on the discussions of realism and antirealism in the sciences. In my readings, I have come across the work of two Christian philosophers who argue against realism: First J.P. Moreland, who argues for an eclectic view of looking at the results of science, choosing between a realist or antirealist perspective depending on the subject at hand, and second, Bas van Fraassen, who holds a view called constructive empiricism. Both of these views would be in opposition to my earlier paper on the issues of antirealism. In addition, some philosophers who attack realism, as illustrated by the quote from Aurthur Fine above, seem to argue that physicists themselves are the ones who have promoted antirealism. If I am going to continue to insist that antirealism is a deficient perspective (as I stated in my earlier paper), I must contend with these viewpoints.

Since as Christians we must deal with science, the question arises which view is better suited to help us carry out the purposes of science? I will be arguing for a view I term Humble Realism, which I believe takes into account who we are in Christ and helps to deal with the real difficulties in realist views of science. In order to explain why I am taking this view, I will look at antirealist views of several philosophers, then at the problems of realism both from the view of philosophy and physics, express why I feel realism is so necessary to the sciences and then lay out my views of Humble Realism.

2 The Antirealism of Moreland, van Fraassen, and Fine

Before turning to the antirealist views, a more clearly stated delineation between the realist and antirealist views is helpful. A more formal way of defining realism would say a realist believes that science is telling us the story about what is really present in reality, and theories in science are discoveries about reality not fables we create. As Bas van Fraassen states when discussing how a realist would view the role of science,

> Science aims to give us, in its theories, a literally true story of what the world is like; an acceptance of a scientific theory then involves the belief that it is true.(van Fraassen, p. 8)

So realism would claim at one level that as theories are borne out in experiments, we can have more confidence in the view of reality they paint. (There are obvious variations in how strong a confidence one has.) In opposition, antirealism would claim that the success of a theory does not imply that its picture of reality (especially at the level of non-observable entities, such as electrons or atoms) is true. J.P. Moreland lays out a good contrast between the two, saying

> Scientific realism, roughly defined, is the view that successful scientific theories are true or approximately true models of the theory-independent world. A number of antirealist approaches to science agree that science works—it solves problems, gives us predictions, allows us to control nature and describe observation simply—but that its success does not indicate that scientific theories are true or approximately true.(Moreland, p. 13)

2.1 Moreland's eclectic view

In *Christianity and Science* Moreland advocates for an eclectic perspective toward the issues of realism and antirealism. In his work he presents a good discussion on the issues of theory acceptance and the possible viewpoints in the realism/antirealism discussion. It is his statements on how to deal with the integration of science and theology which intrigue me. He states:

> ...attempts to integrate science and theology, including efforts to resolve apparent conflicts between them, should not automatically assume a view of

> science known as scientific realism. ... An eclectic model of science on a case-by-case basis, should be used to integrate science and theology.(Moreland, p. 13)

Part of Moreland's justification for taking this approach is because in the past many scientists have taken what would be called a phenomenological approach to their science, and that they and some philosophers do not see science through a realist prism, as he states:

> We will see ... that a number of scientists and philosophers do not think that science necessarily attempts to understand reality. Much of what we would want to count as science involved scientists who merely tried to "save the phenomena", ... (Moreland, pp. 21-22)

In the end, Moreland gives a tentative conclusion,

> I see no reason why one cannot adopt an eclectic approach to science that adopts a realist/antirealist view on a case by case basis.(Moreland, p. 203)

His reasons for this approach are varied, including the inherent problems that realism faces (which I will discuss later) as well as some stunning failures of realism (in advocating theories that turned out later to be false, which again I will discuss), yet he acknowledges that there is merit in the idea that with our senses we are able to go beneath the level of the observable.(Moreland, pp. 203-204). I believe, however, that the dominant reason Moreland chooses this approach is not because he wants to understand how science is done (or should be done), as he states

> In sum, an eclectic approach to the realist/antirealist debate deserves serious consideration and could provide a conceptual framework for developing one's view about the integration of science and theology. For example, when science and a theological statement or biblical interpretation come into conflict part of the solution may lie in adopting an antirealist view of the scientific statement.(Moreland, p. 205)

Moreland's desire is to head off possible conflicts between interpretations of science and interpretations of scripture by using antirealism to avoid the issue.

Moreland's approach, however, is essentially no different from that of the Jesuits in the time of Galileo. To avoid the conflict between a heliocentric model of the solar system and the Catholic interpretation of geocentricism, the Jesuits embraced fictionalism and chose to use the scientific model but did not give it any credence as reality.(Ashworth, p. 158) Just as the Jesuit view led to a deficient science, I believe Moreland's proposal is very deficient both in how it deals with the conflict issue, and what it would lead to in science. This approach to dealing with conflict by labeling the other side as useful but not true would seem to deny that we are dealing with interpretations of the two revelations by God, special and general, and that the conflict is between the interpretations of special and general revelation, not between the revelations themselves. His approach puts the onus fully onto the science side, and would seem to support the Jesuit's position in the time of Galileo. For he states:

> *An antirealist approach should be taken toward some scientific theory in those cases where the phenomena described by that theory lie outside the appropriate domain of science, or the scientific aspect of some phenomena is inappropriately taken to be the whole phenomena itself.* (Moreland, p. 206, italics in original)

and to the Jesuits, Galileo's model was outside the proper domain of his science, since the dispute was over which domain (in this time astronomy or philosophy) had the right to say what is real.(Ashworth, p. 158) Since to the Jesuits, Galileo was outside of his appropriate domain, they would be fully justified to embrace fictionalism according to Moreland. Furthermore, those who hold to a fictionalist view of the age of the Earth or Universe (the other example I brought up in my earlier paper) would also be fully justified in their view, since to them Big Bang cosmology is speaking outside the appropriate domain, by talking about the unique creation event rather than with repeatable events.(Broussard, p. 14)

The problem with Moreland's position is in defining "the appropriate domain of science". As Larry Lauden has discussed, the demarcation problem (or defining what science is or is not) cannot be fully resolved,(Lauden, 1988) and this means that the areas science covers are also not clearly laid out. So how do we know when science is "outside the appropriate domain"? It will be determined by our presuppositional views of how we interpret both the domains of science and scriptural interpretation. Mary B. Hesse makes an excellent point about the difficulties to divide the realms when she states:

> All these attempts to divide the provinces of science and religion are dangerous illusions, they are false for science because science has a valid claim to investigate *all* aspects of experience, 'spiritual' as well as 'material', and in new sciences like brain physiology and para-psychology is making good its claim; they are false also for Christianity, because they deny the concern of the Christian God for the material world which He has created.(Hesse, p. 155)

Regardless of how one allocates domain here, it would seem to be clear that Moreland's definition of when to invoke antirealism is ill-defined, but more importantly antirealism is a view that leaves science impotent. I will concur with Moreland that at times scientists have claimed that the physical description of phenomena is all there is (such as his discussion about brain function) and that is inappropriate. However, an antirealist approach to the model will *not* change anyone's view that science has claimed too much. To me, it would be better to discuss with the science community why they limit the phenomena to their particular model.

2.2 Bas van Fraassen's constructive empiricism

The description of van Fraassen's view that I give here has been taken both from Moreland's text as well as van Fraassen's book *The Scientific Image*. To van Fraassen,

> Science aims to give us theories which are empirically adequate; and acceptance of a theory involves as belief only that it is empirically adequate.(van Fraassen, p. 12)

This is constructive empiricism, which is in the realm of antirealism. Van Fraassen's antirealism is tied to his view of the observable/nonobservable debate in the understanding of theories of science, as he states in his view of what science does:

> ...scientific activity is one of construction rather than discovery; construction of models that must be adequate to the phenomena, and not discovery of truth concerning unobservables.(van Fraassen, p. 5)

As I discussed in my earlier paper, the status of nonobservable entities that occur in scientific theories continues to be a major issue. Van Fraassen is quite clear on what defines an observable in his model.

> X is observable if there are circumstances, which are such that, if X is present to us under those circumstances, then we observe it.(van Fraassen, p. 16)

How does one observe, however? van Fraassen lays this out by stating,

> The term 'observable' classifies putative entities (entities which may or may not exist). A flying horse is observable- that is why we are so sure that there aren't any- and the number seventeen is not. There is supposed to be a correlate classification of human acts: an unaided act of perception, for instance, is an observation. A calculation of the mass of a particle from the deflection of its trajectory in a known force field is not an observation of that mass.(van Fraassen, p. 15)

This viewpoint would of course limit any observable to what we can perceive unaided, which I believe would imply that van Fraassen would not take X-rays, ultraviolet or radio waves as observables, since none of these can be observed by us unaided. His point about the mass of a particle would also imply that his weight is not an observable if he uses a bathroom scale, since bathroom scales do *not* measure your weight, but instead the normal force the scale exerts on you as you stand on it. Even simple measurements that we take for granted must be called into question such as the speedometer on your car. The speedometer does not measure your speed, but is correlated to the rotation rate of your tires. In the latter two cases, under certain assumptions, they will measure what you want, but my point is if van Fraassen limits himself as above, then none of these examples are observables.

The available scale of the observable is also an issue here. To van Fraassen something is observable if under some circumstances, we could observe it, such as his example of the moons of Jupiter.(van Fraassen, p. 16) Things that we cannot ever view with unaided eyes cannot be called observables. Van Fraassen sets humans as the scale of our measurements, when he says

> The human organism is, from the point of view of physics, a certain kind of measuring apparatus.(van Fraassen, p. 17)

van Fraassen's model denies the reality of anything in science that does not fit into his observable category. As he states:

> I wish merely to be agnostic about the existence of the unobservable aspects of the world described by science ... (van Fraassen, p. 72)

Again, as in Moreland's case, his reasons for choosing a view that denies the ability of science to seek for truth seem based not on a desire to understand science better, but to avoid in this case metaphysical issues. Mary B. Hesse makes this point in her discussion of realism and positivism (a philosophical system popular in the earlier 1900's that was antirealist in its views of science), saying

> The realist will talk about 'disclosing the secrets of nature', and will accuse the positivist of regarding science as a trivial game with symbols, while the positivist calls science 'the economy of thought', and accuses the realist of multiplying entities without necessity and talking metaphysical nonsense.(Hesse, p. 148)

Beyond the problems with antirealism in this view, I am more troubled by van Fraassen's scale chauvinism that is so present in his model. Scale Chauvinism, discussed in Joel Primack and Nancy Abrams' *The View from the Center of the Universe*[1] is one of their "mental muddles" that we humans apply to our view of the universe. The first is Scale Confusion, which is our tendency to apply "laws and understandings appropriate to one size scale to phenomena on another scale where those laws and understandings don't apply."(Primack & Abrams, p. 168). This is a common problem in looking at sciences, and is closely related to the second muddle, Scale Chauvinism. As Primack and Abrams see it,

> We propose the name Scale Chauvinism for the natural assumption that the way things look on some particular size scale is fundamental and everything else can more profitably be viewed from this fundamental point of view. The most common chauvinism, of course, is chauvinism of the human scale.(Primack & Abrams, pp. 171-172)

They discuss how others have been scale chauvinists with other scales, such as Richard Dawkins using the DNA scale as normative. For van Fraassen, if the object under discussion is not on his scale, it cannot be an observable. I appreciate van Fraassen's view that in science (and all human interaction) we form the epistemological community, but his view goes beyond that when he says that only our scale is truly knowable and in essence denies that which cannot accommodate to our scale. I would agree that the human race is primary in God's view, but God's creation is clearly not limited to our scale.

I have presented the antirealist views of two Christian philosophers to better understand why they accept them and to give some critique of their views. As Moreland points

[1] This book is a fascinating look not only at the complexities of the universe but also how it is viewed by some in secular science. Though there is much to argue against, it does have much to ponder.

out, several philosophers have embraced antirealism, and in particular, several physicists have as well. I want to look now at how this latter issue is used by Arthur Fine to justify turning away from realism.

2.3 Is Realism Dead? The View of Arthur Fine

In his work on philosophy of science, Arthur Fine makes the startling claim that,

> Realism is dead. Its death was announced by the neopositivists who realized that they could accept all the results of science, including all the members of the scientific zoo, and still declare that the questions raised by the existence claims of realism were mere psuedoquestions. Its death was hastened by the debates over the interpretation of quantum theory, where Bohr's nonrealist philosophy was seen to win out over Einstein's passionate realism. Its death was certified, finally, as the last two generations of physical scientists turned their backs on realism and have managed, nevertheless, to do science successfully without it.(Fine, p. 1186)

In Fine's work, he uses relativity and quantum mechanics (two theories that have changed our view of reality so greatly and have done so much to advance technology) to show that realism is not needed, as it had no impact on the development of these theories. In the case of relativity, his claim is that Ernst Mach (who was an advocate for logical positivism and antirealism) had a strong influence on Einstein, even up to the formation of general relativity in 1915. In Fine's view, Einstein did not become a realist until about 1920. Fine sees the struggles Einstein had with Bohr over the status of quantum mechanics as a struggle over realism, saying "His [Einstein's] subsequent battle with the quantum theory, for example, was fought much more over the issue of realism than it was over the issue of causality and determinism (as it is usually portrayed)".(Fine, p. 1194) In the case of quantum mechanics, Fine's view of the history of the theory's development and subsequent pedagogical issues is quite revealing:

> ...this nonrealist position was consolidated at the time of the famous Solvay conference, in October of 1927, and is firmly in place today. Such quantum nonrealism is part of what *every* graduate physicist learns and practices. It is the conceptual backdrop to all the brilliant successes in atomic, nuclear and particle physics over the past fifty years. Physicists have learned to think about their theory in a highly nonrealist way, and doing just that has brought about the most marvelous predictive success in the history of science.(Fine, p. 1195, italics added)

Statements like the above are likely what Moreland has in mind when he justifies antirealism on the basis of philosophers and scientists not seeing science as understanding reality. Fine is using the supposed antirealist views of Einstein before 1920 to justify why realism is no longer needed. However I contend that Fine is seriously in error in his argument and that instead Einstein was a realist long before 1920.

When we look at Einstein's life, there is no doubt that he was heavily influenced by Mach before he developed relativity, as Fine states. However, what Fine carefully neglects is that at the same time Einstein was publishing his work on special relativity, he was also publishing his explanation of the photoelectric effect, where he applied Planck's trick of putting energy into discrete units. Unlike Planck, as David Lindley claims, to Einstein "[t]he division of energy into small units was not merely a mathematical trick but in truth represented a new and astonishing discovery about the physical nature of electromagnetic radiation. The quanta truly are atoms of energy." (Lindley, p. 209) In addition, in this same year, (Einstein's *annus mirabilis*, 1905), Einstein published his paper explaining Brownian motion on the basis of Ludwig Boltzmann's kinetic theory, assuming the existence of atoms. This paper was verified by the work of Jean Perrin in 1908, and the reality of atoms became reasonable, as David Lindley states: "For many doubters, Einstein's analysis, especially when it was backed up by Perrin's measurements, constituted the first empirical demonstration that atoms were real—tiny, hard mobile objects, moving in predictable ways according to Newton's laws." (Lindley, p. 211) If Einstein were a strong believer in Mach's antirealist philosophy, it would be hard to believe he would dabble in what Mach thought was a waste of time, trying to estimate the size of those "make believe" atoms. Einstein, who did continually praise Mach's insights into physics, was, however, not enamored with Mach's philosophy, as he stated in a lecture before philosophers in 1922: "Mach was as good at mechanics as he was wretched at philosophy. This short-sighted view of science led him to reject the existence of atoms." (Pais, *Einstein*, p. 283) It is clear that Fine has seriously misrepresented Einstein, who showed realist attitudes long before 1920.

When we look at quantum mechanics and Fine's argument, one might feel that he has a point. Here the issues of reality have been battled over, as Werner Heisenberg is famous for stating "Atoms are not things." There is no question that Bohr and Einstein wrestled over quantum mechanics, which Fine claims was "... more over the issue of realism than it was over the issue of causality and determinism...". The question here is, is Fine being honest in the appraisal of the conflict? We can look at another perspective, given by Nick Herbert in his work *Quantum Reality*. Here Herbert lays out some of the possible interpretations of quantum mechanics. In discussing Bohr's view of how to interpret quantum mechanics (called the Copenhagen interpretation), he gives a clear statement on how Bohr viewed reality:

> The Copenhagen interpretation, developed mainly by Bohr and Heisenberg, is the picture most physicists fall back on when you ask them what quantum theory means. Copenhagenists do *not* deny the existence of electrons, but only the notion that these entities possess dynamical attributes of their own.(Herbert, pp. 158-159, italics added)

What is the struggle that quantum mechanics introduced? Perhaps Herbert has it wrong, and Fine is correct in his view that the current portrayal has hidden the real struggle. Bohr is famous for statements such as

> There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how

> nature is. Physics concerns what we can say about nature.(Pais, *Bohr*, pp. 426-427)

which sounds like an antirealist position. However, if one examines Bohr's life and study of quantum mechanics, as was done by Abraham Pais in his biography of Bohr, one does not see the elements of antirealism so prevalent in Ernst Mach or van Fraassen. He clearly thinks electrons exist, but just not as the objects that Einstein held. For example, Bohr was very involved in the understanding of radioactivity, associating it with the nucleus, and in studies of the neutron, as well as trying to understand the workings of the atomic world. I believe that what Bohr was dealing with is the issue of our language to describe the quantum world. As Bohr stated, "An independent reality in the ordinary [that is classical] physical sense can . . . neither be ascribed to the phenomena nor to the agencies of observation." Even Heisenberg, who is usually painted with an antirealist brush, is seen to be working on how the neutron could be seen as part of the nucleus and thereby solve some of the outstanding problems of the time.(Pais, *Bohr* p. 332)

When we look at the history of how Einstein dealt with quantum mechanics, as done in Pais' biography of him, it is clearly seen that the main issue was causality and determinism, in disagreement with Fine's point. When Einstein was working out the implications of the theory of light quanta (photons) in 1917, he was struck by the fact that there is "a weakness of the theory . . . that it leaves the time and direction of elementary processes to chance".(Pais, *Einstein*, p. 411) In 1920, he expressed his reservations to Max Born on these issues, writing

> That business about causality causes me a lot of trouble, too. Can the quantum absorption and emission of light ever be understood in the sense of the complete causality requirement, or would a statistical residue remain? I must admit that there I lack the courage of a conviction. However, I would be very unhappy to renounce complete causality.(Pais, *Einstein*, p. 412)

It is clear that determinism was seen by others as a major issue, as Born discussed in his famous paper in 1926 on the meaning of the Schrödinger wavefunction, writing ". . . I myself am inclined to renounce determinism in the atomic world, but that is a philosophical question for which physical arguments alone do not set standards." (Pais, *Einstein*, p. 442) So again, although struggles over realism may have been present at that time, the main issue for Einstein was the loss of causality and determinism, in opposition to Fine's argument.

I want to talk about how quantum mechanics has changed our views of reality, but before I turn to that, I have to also deal with Fine's point that all graduate physics students are soaked in quantum nonrealism. I have looked at textbooks dating from 1950 till the present on quantum mechanics. There are often statements dealing with the reality of the wavefunction, as I will talk about later, but in none of them is a "quantum nonrealism" present. In my own field, I have not run across any physicist who is a nonrealist when it comes to the nonobservables dealt with in the theories we use. Fine's attempt to declare the death of realism by appealing to physicists is a failed attempt to justify his own belief structure.

3 The Problems with Realism

There are actual issues with realism that have resulted in it not being embraced by philosophers and scientists. Larry Laudan in his work on realism has discussed some of the philosophical problems that it has (Here I have only given the main ones). We consider a general theory of science that contains unobservable entities and claim to view the theory in a realist manner. First, assuming these unobservable entities actually exist, this in no way guarantees that the theory in its entirety is true, nor does the validity of the theory guarantee the existence of these unobservable entities. Second, if we qualify our realism and instead say the theory is approximately true, we find a definition of what this means very difficult. Just how do we quantify approximately true (or not quite false?) Without a measurable quantity, how do we compare different theories? Third, how can realism explain the fact that many theories have made successful predictions but were not true (such as Bohr's model of the hydrogen atom which gives the right energy levels with incorrect assumptions, or Sommerfield's calculation of the splitting of the energy levels in hydrogen by assuming elliptical orbits for the electrons, when now we say the splitting is due to spin-orbit interactions between the electron and proton)? Fourth, is the view that newer theories incorporate the older ones really true, or is it really clear that newer theories can truly explain why older ones either succeeded or failed? Finally, can realism truly establish that non-realist views are unable to explain the success of science?(Laudan, 1981 p. 1131) None of these questions have complete answers in realist views.

Realism has even more problems. Del Ratzsch has pointed out that in any model, the fact that data always underdetermine the theory is a crippling blow. There are always alternative explanations that could predict the same data. Data never make a "perfect" match to a model. In addition, if our desire is to confirm the existence of the nonobservables in our theory (such as electrons), the issues of confirmation have no clear resolution, because we do not have "direct" access to electrons (since they are not on our scale). We must use indirect methods, and so leave open the possibility that the connections we use to draw our inferences are not fully correct, which is the classical prisoner-guard problem.(Ratzsch, pp. 86-91) Even beyond the challenges to realism from the philosophers, physics itself has seemed to strike a blow against it, just as Fine claimed. We must look at the issues that physics brings up for realism, in particular, quantum mechanics.

3.1 Quantum Mechanics and Challenges to Realism

There is no question about the massive changes that quantum mechanics has brought to our view of reality. These changes have brought much discord to our scale chauvinistic minds. We are so caught up with how objects behave at our scale, that our belief that all scales should conform to ours locks us into the wave/particle dialectic. We think what is one cannot be the other. Atoms, electrons, etc., should act like nice orderly billiard balls, behaving as Newton's laws tell us they should. So we build models of how things on smaller and smaller scales should behave and we find they fail miserably.

Quantum mechanics comes along and behold, its predictions bear out with what we can measure. However, it asks a great deal of us. First, it provides no ontology to us. There is a wavefunction describing the probability of finding the object under discussion, which must satisfy the Schrödinger equation (in the non-relativistic limit). For a single particle the equation is

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t) + V(\vec{r},t)\Psi(\vec{r},t) = i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t}.$$

Quantum mechanics states that the wavefunction, Ψ, contains *all* the information one can know about the behavior of the particle, given that the information put into the equation is accurate. (In the above equation, $\hbar$ is Planck's constant over 2π, m is the mass of the particle, $i = \sqrt{-1}$, ∇^2 deals with how the wavefunction changes in space, $\partial/\partial t$ deals with how the wavefunction changes in time, and $V(\vec{r},t)$ is the potential energy the particle experiences at a particular location and time.) What is the status of this wavefunction? Is it an actual wave that we can measure? Is it real or just a calculus tool? In E.L. Mascall's work *Christian Theology and Natural Science*, he discusses how some view the terms in quantum physics in an non-realist manner. He states:

> All that is important is that we shall understand the function of theoretical terms in the calculus which we use, and our answer to the question "Do electrons really exist?" is simply to explain the functions of the words and other symbols used for electrons in the calculus which is interpreted as the deductive system of contemporary atomic physics. As an example of a symbol which he (R.B. Braithwaite) believes every atomic physicist would agree in interpreting in this way he gives the ψ-function of Schrödinger, ... The statement is simply a formula in a calculus, and from it, by applying the rules of the calculus, we can derive sentences which do describe observable events... (Mascall, pp. 70-71)

There has been a great deal written on the nature of the wavefunction. Van Fraassen for example has several sections on quantum mechanics (showing his understanding of the mathematics of the field). (van Fraassen, pp. 61-66, pp. 170-177) What he focuses upon is how the wavefunction connects to measurable quantities through Born's interpretation, in that the square of the wavefunction relates to the probability of finding the object described by the wavefunction. This is the standard view in quantum mechanics as shown in Tipler and Llewellyn's text on modern physics, a standard book for introducing quantum mechanics. Here they state, "The wave function is a *computational* device with utility in Schrödinger's theory of wave mechanics. Physical significance is associated not with Ψ itself, but with the product $\Psi^*\Psi = |\Psi|^2$, which is the probability distribution $P(x,t)$ ..." (Tipler and Llewellyn, p. 246, italics added) So to some, the wavefunction is simply a calculational device, not having "physical significance". I will come back to this point later with an example from my field to say why I feel that view is not the entire picture.

Next, quantum mechanics is unashamed in stating that we cannot, under any circumstances, measure pairs of certain quantities (such as location and momentum, energy and time) to any degree of accuracy that we want. This result is the famous Heisenberg uncertainty relation, given for these cases as

$$\Delta x \Delta p \geqslant \hbar/2.$$

Why is this so? One can claim it is because the object that we thought of as particles (little billiard balls) sometimes behave as waves and things we thought of as waves (like ocean waves) sometimes behave more like discrete bits, like say, a particle. So, what are they? This is the famous wave-particle duality. Herbert in his *Quantum Reality* calls subatomic entities "quons" in order to have a name for it. A quon is just the name for an entity that exhibits both particle and wave properties, but never both at the same time. Classically, this behavior would be completely ludicrous.

Last, quantum mechanics ignores the issue of causality in the cases when there are possible future outcomes. It is very interesting that although the wavefunction calculation is completely deterministic, all the wavefunction gives us is the probability of a possible outcome. There is nothing in the theory that tells us why one outcome happened rather than another. It is quite silent on this point. As the book *The Quantum Challenge* phrases the issue when discussing the question on which slit does an electron go through in the classic double slit experiment:

> But what is the insight provided by quantum mechanics? The quantum-mechanical account we have given of particle interference has managed to avoid asking the very question we would most like to see answered. Furthermore, it has avoided the question by the very nature of the terms of analysis it employs.... Quantum mechanics' avoidance of this question, far from being a defect, is actually the theory's greatest virtue.(Greenstein and Zajonc, pp. 20-21)

There is no doubt in most physicists' minds that quantum mechanics has, as stated before, undone our traditional views of causality and determinism, which undermines any classical view of realism based on a Newtonian model. This disruption of classical views causes many to have severe problems with quantum mechanics. An example of a Christian dissenter is R.C. Sproul, who in his work *Not a Chance* had some critical things to say about the field. Even though realism is fraught with problems both from the standpoint of philosophy and physics, I feel that there is a way forward on how we can view realism. First, however, I want to clearly lay out why I feel realism is so crucial in order to do science. One of the clearest reasons to me is the issue of fruitfulness.

4 Fruitfulness in the Sciences

What do I mean by fruitfulness? I am thinking specifically about instances in science where there has been an advance in empirical adequacy in a totally different arena, due to a new connection made because of a realist view of the models of science. This is similar to what Del Ratzsch discusses in his work *Science and its Limits*, where he says "If various theoretical principles are not on the right track, it is difficult to account for the success science has had in predicting entirely new phenomena, phenomena often *observationally unrelated* to either the phenomena for which the theory was originally proposed to anything else previously known." (Ratzsch, p. 81, italics in original) I will give several examples from physics. First we look at the kinetic theory of matter. This field is one where historically there has been a continual struggle between realism and antirealism. Ludwig Boltzmann, who championed the realist view, embraced the idea that matter was made of objects that could be modeled as three dimensional billiard balls. The conclusions he drew out, based upon the reality of that assumption, led to many advances in the fields of thermodynamics and statistical mechanics. In particular it was his work on modeling the statistics of these atoms that brought the concept of entropy into the prominence it now has (with applications to many areas outside of this original study), which would have not been done from an antirealist viewpoint

Second, when Max Planck in 1900 put forward his explanation of blackbody radiation[2] he introduced the idea that energy could only be exchanged between the electromagnetic field and matter in discrete amounts, whose size was determined by the frequency of the radiation.(It is interesting that Planck used Boltzmann's mathematical techniques to attack this problem.) Planck introduced this concept, later named the quanta, mainly as a mathematical trick to see if the problem could be solved via a different route. It is not clear that he saw this feature as being actually part of reality, so to Planck this could have just been a calculational tool, as Lindley states: "Planck believed at first, and for some time afterward, that this was in some way merely an oddity of the manner in which he had done the calculation and not that it had any fundamental physical meaning."(Lindley, p. 208) Albert Einstein is the one who looked at the model of Planck and conjectured that if this principle of discrete energy was actually present in reality (photons) then it would explain the enigma of the photoelectric effect[3] by hypothesizing that not just exchanges but the electromagnetic radiation itself was quantized. At the time, no scientist saw a connection between the two problems of blackbody radiation and the photoelectric effect. It was *crucial* in the advance of our understanding that the reality of quantization was taken, for without that step, what possible connection could have ever been drawn?

This story does not end there, however. Einstein continued to push the realism envelope, by saying in essence, what if all vibrations are quantized? A conundrum in my field, condensed matter physics, was the explanation of the temperature dependence of specific heat in materials.[4] The understanding of the day, based upon the atomic model, coupled with Boltzmann's kinetic model and theories of elastic properties, gave a reasonable value for the specific heat of materials near room temperature,[5] but as the temperature is lowered, the specific heat began to decrease. This behavior was totally unexpected, and had no solution within the physics of that time. Einstein's insight was

[2]The electromagnetic radiation given off by all objects above absolute zero temperature. It is most commonly observed by seeing hot objects glow a dull red, or the color of a candle flame.

[3]The property that metals emit electrons when bombarded by ultraviolet light.

[4]Specific heat is the measure of the energy it takes to raise the temperature of 1 gram of the material 1 Kelvin

[5]Actually only for insulators, as for metals no one could understand why the electrons did not contribute. That solution took a little longer.

to accept the reality of quantization and apply it to the vibrations of the atoms in a solid, not just the vibrations of the electromagnetic field. In doing so, he created a model of the specific heat of a solid which gave much better agreement with what was seen. Now, it must be stated that his model is not fully correct, (the empirical adequacy improved from the past, but it still was not satisfactory to the scientists of the day) because of the limitations he put on his model, but not because of the realist view he took towards the physics. The improvement in this area came about with the work of P. Debye, who kept the reality of quantization, but allowed for a more realistic model of the vibrations in a solid. My point again is that it was a realist view of the models that led to the important breakthroughs. I could go on with this area and discuss the success of being a realist and applying quantum mechanics to electrons in metals, which led to greater breakthroughs in our understanding of semiconductors and has given us the computers we so depend upon today.

The third example I wish to bring up is the history of the neutrino. In my view, the history of the neutrino is another triumph of how realism has opened up new insights into science, especially in light of the fact that for many the neutrino is the classic nonobservable. This area is even more technical than the previous ones, but I want to bring it up especially since realism is seen as more threatened at the subatomic level. Radioactive beta decay was being studied right after the discovery of radioactivity. In beta decay, a nucleus emits a high energy electron and the nucleus ends up with one less neutron and one more proton in the end. We now know the reaction can be viewed as a neutron decaying into a proton, electron, and anti-neutrino.[6] However in the time of the 1910's, all that was known was that some radioactive nuclei gave off high energy electrons. From the principles of momentum and energy conservation, it could be easily calculated just how much energy the electron would have when it left. The problem was that when the energies of the electrons were measured, they ranged from essentially zero up to the calculated value. So it seemed that conservation of energy was not working at the scale of the nucleus. For some physicists, this was an acceptable view, since at the time many other cherished ideas were being demolished by the theories of relativity and quantum mechanics. For others, there was an emphatic view that conservation of energy had to be true. Still the question remained as to the explanation for the discrepancy. It was Pauli, who in 1930, proposed a startling conjecture. He said that when the decay happens, there are two particles given off by the nucleus, one being the electron and the other a new particle, which had to have no charge, and was so weakly interacting that it would not be easily seen. We now call this the neutrino (Enrico Fermi's name for it, meaning little neutral one), but at the time it seemed a foolish idea. Yes, it could explain the conservation of energy puzzle, but only by postulating what would seem to be the ultimate nonobservable. It wasn't until 1956 that Frederick Reines and Clyde Cowan detected the anti-neutrinos being given off from a fission nuclear reactor, allowing the estimation of how weakly interacting they are. Now how has the idea of neutrinos connected to other areas? The reality of neutrinos and their interaction have brought insights into the death of stars, the understanding of the nature of quark families in

[6] Actually the decay is due to a down quark in the neutron decaying to an up quark and emitting a W^- which decays into an electron and anti-neutrino.

the Standard Model of elementary particles, and lately the attempts to understand the rate of heat produced in the Earth's interior due to radioactive decay (Araki *et al.*) to name just a few. For an idea that was greeted with much skepticism, much has been accomplished by viewing neutrinos as real.

The final example I will draw upon is the issue of non-conservation of parity in the weak interaction, put forward by T.D. Lee and C.N. Yang in 1956.(Frauenfelder and Henley, pp. 203-209) The field of high energy particle physics in the experimental arena is dominated by taking electrons and speeding them to velocities very near the speed of light where their energy due to motion is very large and then colliding them together with protons or positrons (which are the anti-particles of electrons). These collisions create other particles which physicists can then study.(I realize that I have already made a great realist leap even in setting this up, but bear with me.) Parity is the behavior of a system when one axis is reversed, for example when one views the system in a mirror. A system has even parity if it looks the same in the mirror as it does in actuality. A system has odd parity if it is reversed in the mirror. A foundational principle before this time was that the fundamental interactions of physics (strong force, electromagnetic force, weak force and gravity) would not change the parity of a system, or they would conserve parity. However at this time, two particles were known, the τ and the θ, which seemed to be the exact same particle, having the same mass, charge, and spin.[7] They seemed identical, yet they decayed (exist for some time after creation and then become other particles) in two different ways, one with even parity and one with odd parity. The time it took for the particles to decay was long enough to know that the weak force had to be responsible for the decay. So the choices were to either say (in my phrasing) God made two of the exact same particle but one he made odd and the other even parity (and there are no other examples of this) or parity is not conserved under the weak interaction (which was repugnant to many physicists). Lee and Yang put forward the idea that the weak interaction does not conserve parity and also made the realist connection by stating how this might be observed in specific experiments. Now if they had been antirealists, it would be empirically adequate to say the mathematics here require this suggestion and that ends the discussion. (In fact it would have been fine from an antirealist view to simply state these are two different phenomena and leave it at that.) However that was not the end, for one of the experimental suggestions they made was taken up by C.S. Wu and her collaborators, believing that the weak interaction in one area should be the same as another. They looked at beta decay of cobalt nuclei, which physicists have seen is also due to the weak interaction and in this example involves the emission of a high energy electron from a radioactive cobalt nucleus, which then becomes a nickel nucleus. By aligning the spin of the cobalt nuclei in a very intense magnetic field at low temperature, they were able to show that there was a significant difference in the number of electrons emitted along the field direction compared to opposite it. The two rates of emission should be the same if parity is conserved. This section is a bit more technical but the point is that the reality of the weak interaction had to be assumed if

[7]Spin is a quantum mechanical property of the particles, and though the history of it came from the idea of a spinning particle, we now know that cannot be the actual behavior. It is another of those terms that I am sure are real, but I cannot give a complete description.

it applies both to phenomena in a huge accelerator lab and to the radioactive decay of cobalt. Nothing would tie these together in the mind unless there is a belief in underlying order that can be studied and understood to some degree.

Have there been breakthroughs without realism? Yes, for example Planck's model of blackbody radiation was given by using a mathematical trick, to which he assigned no reality. (I would point out he did use realism in his views of the materials he was modeling). Murray Gell-Man's Eight fold way was an attempt to understand the plethora of particles found in high energy physics (such as Δ, Σ, Ξ, and Ω) by postulating a mathematical object which had symmetries that seemed to be present in the particles.(Tipler, pp. 643-645) Again, however it was the realist connection that the properties could be explained by assuming that these particles were themselves composed of a much smaller set of particles (quarks) which obeyed certain rules.

Van Fraassen has a definite point that empirical adequacy is an important goal in science, because without it, we could not use our science in our call to be better stewards. Empirical adequacy is definitely a major issue in the debate about global warming today, for example. We would like a model that can accurately account for the effect of certain greenhouse gases on our average temperatures. Again, empirical adequacy would be very helpful in our models of how materials behave in order to create a far more energy dense battery material, allowing for fully electric cars with ranges in excess of 50 miles. In science, using empirical fits to data (also known as phenomenological science) is what one has to do at times. As an example, in looking at the scattering of electrons in antimony, the group I was involved with used an empirical fit to the data[8] in order to model the behavior. I can still remember the team leader exclaiming "Nature does not go as $T^{3.3}$!" showing his belief in the simplicity of physics. Nonetheless, the data was published with that "unnatural" expression.(O'Hara) Recently in my work on the behavior of certain oxides in magnetic fields(Broussard, 1999), I have engaged in phenomenology in understanding their temperature dependence of the resistivity and the magnetoresistance (how the resistance changes as the magnetic field is changed). There is no question in my mind that we must have empirical accuracy if we are to be the stewards God calls us to be. However if it remains the only goal in our science, will that encourage the insights that have been such a blessing to us? For instance, when Einstein pondered over the issues of gravity and spacetime, he was not worried about the empirical accuracy of the current theory of gravity. He was wrestling with understanding how to incorporate a gravitational field into relativity theory in a unified mathematical system. This work led in 1915 to the development of his general theory of relativity, which is now used to give Global Positioning Systems accuracy of better than 15 m. Here we have a big gain in empirical adequacy, that came from trying to understand the nature of reality.

[8]In particular the temperature dependence of the anomalous skin depth.

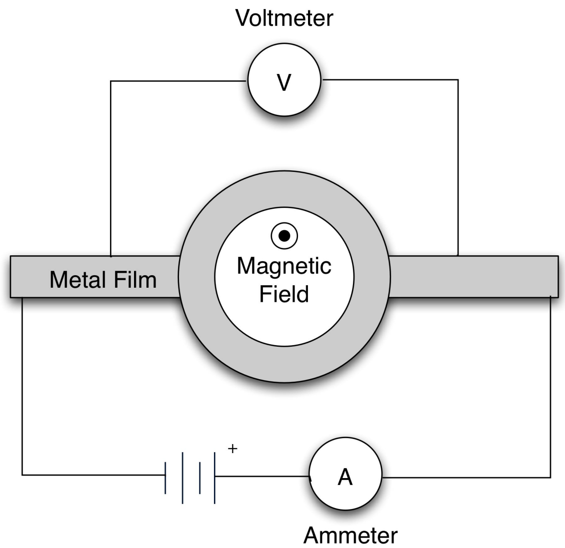

Figure 1: Metal film patterned with a ring shape in a varying magnetic field. Resistance of film measured with Ohm's law.

5 The Nature of the Wavefunction and Status of Nonobservables in Condensed Matter Physics

So much of my area (condensed matter physics) is dominated by electrons and quantum mechanics and the associated wavefunction. We have seen that many view the wavefunction as an unreal calculational tool. My studies in this field give me a different perspective, which I want to lay out. The wavefunction at a point in space is a complex number, which cannot be measured directly. A complex quantity however has a phase as well as its magnitude, which means we could write $\Psi(x,t) = f(x,t) + ig(x,t) = \sqrt{|\Psi|^2} \exp i\theta$ where $i = \sqrt{-1}$ and θ would be the phase of the wavefunction.[9] We have already stated that the magnitude of the wavefunction connects to a measurable quantity, the probability of finding the particle at a point. In my example we are going to see that the phase of the wavefunction also connects to measurable quantities. To help with my example let me give a simple description of the measurements one would make. If we put a current through a piece of metal, as is done in a light bulb, it takes some energy to keep the current flowing. We say the metal has resistance to the flow of current. We calculate the resistance of the metal using Ohm's law ($V = IR$), by measuring the current going through the metal (I) and the voltage change in the metal (V). The voltage change is related to the energy it takes to keep the current flowing. (Notice that since all these measurements require other devices, such as a voltmeter or ammeter, to van Fraassen, they are *not* observables.)

My specific example is the Aharonov-Bohm effect, which can be seen in a metal film that has been patterned as in Figure 1 above. The measurement is a manifestation of the famous double slit experiment, where a wave (such as sound or light) passes through

[9] Here, $\tan\theta = \frac{g(x,t)}{f(x,t)}$, which is itself a function of position and time.

two parallel slits and produces an interference pattern on a screen (regions of light/dark in the case of light, or loud/quiet in the case of sound). This pattern is due to waves coming from the two slits combining and either adding together (peak lines up with a peak) or canceling out (peak lines up with a trough). For the double slit experiment, the mismatch is due to the different distances the waves travel. Here in the Aharonov-Bohm effect, the electrons are the waves who go through two different paths around the loop and interfere. However instead of different distances causing the interference, here the adding or subtracting of the waves is due to the interaction of the electrons with an applied magnetic field, which adjusts the phase, or the term θ in the previous paragraph.[10] In order to see this effect, the metal film shown in Figure 1 has been produced with very specific properties. Why? Well, under a realist perspective, the electrons in the metal, which go mainly from left to right in Figure 1, like to see a periodic array of the atoms as they move. When that regularity in the metal is disrupted by say the wrong atom in a spot (impurities) or the vibrations of the atoms due to temperature, the electrons find it harder to flow from left to right. This causes resistance, but more importantly, it can mask the effect the magnetic field has on the phase. Therefore first the metal film must be prepared with very low impurities and the temperature must be kept very low to allow the electrons an easy path from the left to the right.[11] Next, the loop is prepared so the electrons, which have wavelike behavior, go around *both* sides of the loop as they go from left to right. Finally, we apply a magnetic field that is confined to the interior of the loop in Figure 1 so the electrons do not "feel" the magnetic field (There is no field in the metal film, only in the opening of the loop). The flow of electrons going from the left side of the loop to the right side is determined by the probability of the electrons going from one side to the other, and since the electrons, with their wavelike properties could go through both sides of the loop, there will be interference when the waves recombine on the opposite side. As we change the magnetic field, it varies how it affects the phase of the electron waves, which causes a periodic modulation in the probability of the electrons going from the left to the right. This is observed as a periodic variation in the resistance to the flow of electrons through the ring as the magnetic field is varied, as seen in Figure 2 on the next page.

My point in bringing up this (somewhat technical) example is to point out that if these quantities are just a useful calculus it would seem hard to imagine why if we take them as "real", they connect to different "nonobservables" and explain the measurements. In particular when I see statements such as "Science is indifferent about whether electrons really exist..." (statement ascribed to van Fraassen by Moreland, p. 191) I am very puzzled, since as far as I understand how physicists think, to say their modeling assumes the nonexistence of electrons, or the wavefunction, would be ludicrous.[12]

[10] The phase shift due to paths in a magnetic field are given by $\Delta\theta = 2\pi(e/h)\int_a^b \vec{A}\cdot d\vec{l}$ where $\vec{A}$ is the associated vector potential for the magnetic field, $\vec{B} = \vec{\nabla}\times\vec{A}$.

[11] The technical term here is the phase decoherence length which needs to be long compared to the dimension of the path around the loop which is controlled by electron-phonon scattering, while the resistance of the loop needs to be low so the changes are easily observed, which will be controlled by electron impurity scattering.

[12] It is interesting that van Fraassen's view on electrons engendered an article in *Physics Today* cel-

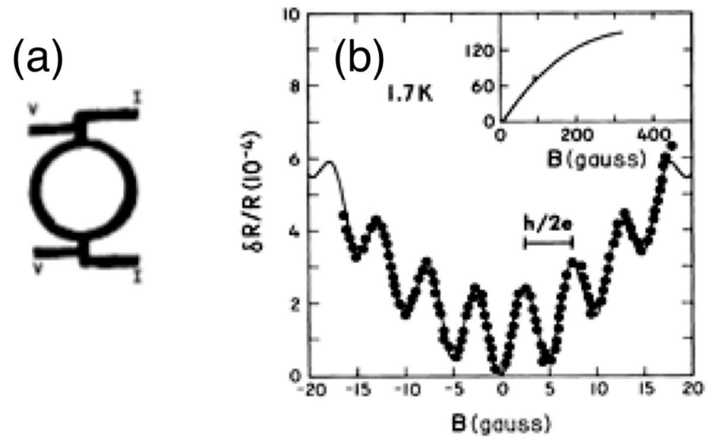

Figure 2: (a)Electron micrograph of an aluminum ring about 1 millionth of a meter in radius and (b) the oscillations in the resistance of the ring as the magnetic field changes. The increase in resistance as the field increases is due to the finite magnetoresistance of the material, which would be present regardless. Figure taken from the article by Chandrasekhar *et al.*

In my field of condensed matter physics there are many entities whose reality is often questioned. Condensed matter physicists talk about the existence of phonons, polarons and magnons, which are the expressions of acoustic, electrostatic, or magnetic quantized wave behavior, respectively. Do I view them as "real"? Certainly they connect to so much in my area of study. The oxides I spoke about earlier are materials whose behavior is understood by using phonons, polarons and magnons and the interactions between them. The models give much understanding about the changes in their electrical and magnetic properties. In light of that finding, what would be the status of such objects? One possible perspective is to realize that the same mathematical analysis that lead to photons (which seem to have real status in physics circles) produces the same type of quantized objects discussed above. So to a physicist, if photons are real, why shouldn't these be as well? (Even with the attendant difficulties of visualizing them.)

How should I view the reality for other objects in my field? What about Cooper pairs, which form the basis for superconductivity? Are they real? They are electrons paired not in their spatial relationship, but through their momentum. A plot of their momentum would show that at all times they have equal magnitude and oppositely directed momentum.[13] Another major area of study in my field is to understand the nature of the Fermi surface, a surface not in a three dimensional space that we can walk around on, but a surface described in the three dimensional space of momentum for the electrons. The Fermi surface defines at absolute zero temperature those electron states which are occupied by electrons from those that are not. The surfaces have a fascinating

ebrating the 100th year of the electron's discovery, where the author turned the discussion into one on whether van Fraassen exists.(Allan Franklin, "Are there really electrons? Experiment and Reality", *Physics Today*, volume 50, pp. 26-33, 1997)

[13]They are actually connected because one is the time reversed quantum state of the other.

shape but are they real?[14]

A classic example of a situation in my field that would separate realism from anti-realism is the discovery of the fractional quantum Hall effect, observed first by Dan Tsui and Horst Störmer in 1982 and the subsequent explanation by Robert Laughlin in 1983. The Hall effect is the appearance of a voltage across a conducting sample that is carrying a current in an applied magnetic field where the voltage is perpendicular to both the direction of the current flow and magnetic field.(In the example of Aharonov-Bohm effect above, the voltage is oriented in the same direction as the flow of current.) This effect was first observed in 1879 by Edwin Hall and is routinely used today to both measure the concentration of charge carriers in materials as well as measure magnetic fields in a wide range of environments. If one measures the Hall effect in certain materials at low temperatures (say below the boiling point of helium, 4.2 K or -451°F), then the wave nature of the electrons and the interaction with the magnetic field becomes dominant. For samples where the electrons are confined to move in a thin sheet, at high magnetic fields (above 1 Tesla, which is about 40,000 times stronger than the Earth's magnetic field), the Hall voltage behaves in a quantized fashion, which corresponds to the electrons filling up available energy levels. This quantum Hall effect was observed by Klaus von Klitzing in 1980. His observations fit with the predictions of quantum mechanics very well, and these measurements are used now to set the standard for electrical resistance calibration (more empirical accuracy). What was not expected was the work by Tsui and Störmer two years later, when new quantized Hall voltages were found at even higher magnetic field levels. These new levels gave the appearance that if they were due to the same model, then the electrons had to have a charge of less than their normal value and in addition, to a whole range of strange values (1/3, 2/5, etc. of an electron charge) so the electrons had to be changing their charge as the magnetic field changed. How do we explain this? To an antirealist, since the electrons are not real, we just say yes, the terms in the theory have variable values and in this range of parameters we simply adjust them to match the findings and we have empirical accuracy. If this is how science is done, then it would end there, for what would motivate you to seek a deeper connection? If you believe that electrons have a certain charge and only that charge, you would be driven to understand why you are seeing results that instead say, no the charge looks like 1/3 of the original. That is how the science progressed and it was a year later that Laughlin proposed that the electrons and magnetic field form a collective object (a quantum liquid) that has states (again it is a collective object of electron and magnetic field) with 1/3 the charge of an electron. As Philip Anderson states "For a long time, it was not clear whether one had established a physical meaning for these fractional charges, but extensive and patient effort by experimenters such as Tsui and his coworkers has left us quite sure they exist." (Anderson, p. 46) Laughlin's model showed why the ratios where always odd fractions,[15] and experiments have borne out the reality (within an experimental context!) of the fractional charge of the current carriers under the conditions of the fractional quantum Hall effect. My point with this rather long example is to simply show that science does not proceed only on the basis of empirical adequacy, but instead

[14] An interesting website with example Fermi surfaces is http://www.phys.ufl.edu/fermisurface/

[15] This is because the electrons are fermions and obey the Pauli Exclusion Principle

on assuming the reality of the components and seeing what that implies. That effort then does lead to empirical accuracy as Laughlin's work did, far better than simply stating (as an antirealist would have to do) let's just accept the numbers as variables to fill in as we see them.

I realize that even many physicists wrestle with the reality of the entities and behaviors I have described. I am wondering however, if scale chauvinism appears here as well. Is the view of objects in space more privileged than say the view of objects in momentum? We cannot see the latter, as our sight is not tuned for that. In quantum mechanics, the two views are simply complements to each other, with either one being valid for working with the wavefunction. So if physicists have measured the Fermi surface of a compound, do I think it has an objective existence? Is the quantum liquid of electrons and magnetic field less real because I cannot build a simple mental model to imagine it? As I ponder these questions, I keep coming back to the view that God's reality is greater than we can fully know or perceive. So if I can't imagine it, does that exclude it from my consideration? I believe this is an important point to consider.

6 A Possible Way Forward?

As I have examined some of the issues in the realism/antirealism discussion, I have argued that a realist view towards the proposed entities or behavior has been an important catalyst toward advances in physics. Antirealism simply cannot claim any such record. However I realize that for me to promote realism, I must be willing to acknowledge the problems that realism has that I discussed earlier. For example, how do I view theories which we use every day but which we know are *not* complete but are empirically adequate for the task, such as Newton's law of gravity, or the Schrödinger equation? How do we view the entities in our theories, especially in light of how quantum mechanics forces us to not view them as objects of our scale, and then gives no help in how we should view them?

E.L. Mascall, in his work *Christian Theology and Natural Science* offers some guidance on how we could begin to view entities that cannot fit into a realism that requires them to behave like objects on our scale. He states:

> Just as the essence of perception is not sensing objects but apprehending them, even if we can only apprehend them through the mediation of sense, so the paradigm of a real world is not its sensible imaginability but its intelligible apprehensibility. I do not mean by this that anything which can be conceived by the intellect is thereby shown to exist, but I do mean that anything that concretely exists can be grasped by the intellect in its concrete existence. If therefore the universe of modern physics is one in which all attempts to make it intelligible by models of sensory type fail and which requires for its systematisation the kind of concepts that are used by quantum physics, this does not in the least imply that it is unreal or subjective. It simply means that the formulae of quantum physics express the kind of intelligibility that it has.(Mascall, pp. 82-83)

Mascall is allowing that we need not have a mental model of the theory in order to view it in a realist manner, but be able to apprehend it. This approach would then allow me to view concepts such as Fermi surfaces or phonons as real entities and since no mental model is required, this alleviates the problem of imagining just what a phonon looks like. My problem though with Mascall's view is his immediately following statement that "If we adopt some such view as this, I do not think there is anything to disconcert us in the brilliant analysis of Braithwaite."(Mascall, pp. 83-84) That is difficult for me, in light of statements from Braithwaite such as "They (terms such as electron and proton) are used as symbols in a calculus which is to be interpreted as an applied deductive system; they are not understood as having any meaning apart from their place in such a calculus."(Mascall, p. 69) So if Mascall's view means we accept that electrons are merely symbols in our calculations, then in light of all the phenomena I have described that have been successfully studied assuming the electron to be a real entity, not just a term in a calculus, I would not be able to embrace it. However, I do not feel there is a one-to-one correspondence between Mascall's and Braithwaite's view of reality.

Theologically, we must accept the tension between the *Imago Dei* that God has blessed us with alongside the fact that we are limited creatures, which is *also* a blessing. This point was made by M. Elizabeth Lewis-Hall and Erick Thoennes in their article "At Home in Our Bodies: Implications of the Incarnation for Embodiment and Christian Higher Education". In their work, they discuss the struggle with our limitations (mental and physical) in our lives, but how we should reflect upon the fact that God chose to make us limited and declared it "very good". For example they state "Our bodies are part of what reflects God's image. They are not a supplement to our nature" (Lewis-Hall and Thoennes, p.39) and "Our finitude is a created good and can be embraced. ...the incarnation is a radical demonstration of the goodness of human nature in its spiritual *and* physical aspects".(Lews-Hall and Thoennes, p. 41, Italics in original) In this perspective we should not struggle so much to get out of our limited view but understand it as God's blessing. This combined with the noetic effects of the Fall would doom any ability to get to the truth of God's creation in any total sense. If our view of realism demands that our theories are *True* in their entirety,[16] then of course with these realities, we would say we could not be realists. Instead as Morris and Petcher state in their book *Science and Grace*,

> We thus have arrived at a twofold perspective regarding knowledge within a covenantal understanding. On the one hand, we should expect some general principles to emerge from our general knowledge of the covenantal relation with creation, the regularities that we consider as laws ... But on the other hand, we should not expect knowledge in an absolute sense nor in complete detail about these so-called laws. Only God can know His purposes absolutely and exhaustively. This truth demands therefore a humble posture on our part where science is concerned.(Morris and Petcher, pp. 132-133)

We must always as Christians realize that our theories and models will be approximations to reality. In some sense, I see a similarity between how we view the theories of

[16] I use the term *True* in the absolute sense.

science to how we view our faith and creeds. I see them as approximations to the reality of God and His word. By this I do not equate scientific models to our creeds, but in a similar sense, do we feel the Westminster Confession exhausts all of the knowledge of God? Of course not. In a similar (but obviously not equivalent) manner, in science I want to communicate we have some knowledge of the electron, such as its mass, charge, and spin. Although I still may at times think of them as billiard balls, I know they are much more complicated than what has been thought in the past. So my method of viewing science must acknowledge the issues I have discussed, while avoiding statements like van Fraassen's "Whose electron did Millikan observe; Lorentz's, Rutherford's, Bohr's, or Schrödinger's?" (van Fraassen, p. 214) Obviously if electrons do exist, Millikan observed God's electron. The descriptions of electrons (varied as they have been) are ours and they are limited because we are.

As I have tried to show, abandoning realism would seem to impede fruitfulness. Now, van Fraassen claims his model will work toward better science, as he states (somewhat boldly to me)

> There is a totally false issue that tends to be brought up in the connection... So only Realism is a philosophy that stimulates scientific inquiry; anti-realism hampers it.
>
> Paid off handsomely, how? Paid off in new theories we have more reason to believe empirically adequate. But in that case even the anti-realist, when asked questions about *methodology* will *ex cathedra* counsel the search for explanation! ...
>
> I call this a false issue, for the interpretation of science, and the correct view of its methodology, are two separate topics.(van Fraassen, p. 93)

(In this section he is mainly dealing with the issue of explanation as a virtue). His drawing a sharp line between interpretation and methodology I think is naive. How we put what we are doing into our metanarrative will have a strong connection to what we do and more importantly, how we think about it, which is what leads to advances in science (the issue of fruitfulness).

To van Fraassen, this issue of science making advances, or progressing, is not due to the ability of science at getting to the truth of the world. He states

> Well, let us accept for now this demand for a scientific explanation of the success of science.... I would like to point out that science is a biological phenomenon, an activity by one kind of organism which facilitates its interaction with the environment. And that makes me think a very different kind of scientific explanation is required.
>
> I can best make the point by contrasting two accounts of the mouse who runs from its enemy, the cat. St. Augustine already remarked on this phenomenon, and provided an intentional explanation: the mouse *perceives that* the cat is its enemy, hence the mouse runs. What is postulated here is the 'adequacy' of the mouse's thought to the order of nature: the relation of enmity is correctly

> reflected in his mind. But the Darwinist says: Do not ask why the *mouse* runs from its enemy. Species which did not cope with their natural enemies no longer exist. That is why there are only ones who do.
>
> In just the same way, I claim that the success of current scientific theories is no mistake. It is not even surprising to the scientific (Darwinist) mind. For any scientific theory is born into a life of fierce competition, a jungle red in tooth and claw. Only the successful theories survive-the ones which *in fact* latched on to actual regularities in nature.(van Fraassen, pp. 39-40, Italics in original)

From my examples of how science has progressed, I fail to see such a vicious nature active when theories come about. The only places close to this description are Kuhn's perspective on phenomena before a paradigm arises (Kuhn, pp. 10-22) as well in my experience the preponderance of theories attempting to explain the phenomena of high temperature superconductivity. What van Fraassen and Kuhn fail to mention is that the theories are not accepted simply because they seem to explain the phenomena, but because they make future predictions which can be borne out in experiment. So I reject how he views the success of science. From my study, it is because scientists seek to understand the nature of the reality underlying the phenomena. Of course, I still have to wrestle with the fact that it is not always because we are moving closer to the true nature of reality that our theories work. I see the success of science being primarily due to the grace of God and allowing us at times to make progress toward a better understanding of the issue at the nonobservable level. I will discuss this more fully in the next section.

In my view of science, I have to allow for the fact that we are limited and fully immersed in our scale, recognizing that we often suffer from scale chauvinism. The influence this has on us has been discussed in the past by Dr. Mary B. Hesse. In response to the question "Are electrons real?", she replies

> . . . the answer is yes, electrons are real patterns of events in the physical world, but their existence cannot be described in exactly the same way as that of tables and chairs and trees and men. To say that a stone exists is in any case not the same as to say that a man exists. The things we have discovered about electrons, electromagnetic waves and the like, simply mean that these are different sorts of things from those with which we are familiar. Problems about their 'reality' or 'existence' would not worry us if we had not for so long been used to thinking of reality and existence in terms of hard material particles–the sort of existence a stone has, or one of Galileo's smooth balls rolling down an inclined plane.(Hesse, pp. 156-157)

Dr. Hesse recognized the issues of scale confusion and scale chauvinism so prevalent in our thinking. Many of our problems with realism have been our forcing our scale onto the nonobservable entities in our theories (atoms, protons, and electrons as billiard balls, or electromagnetic waves as water waves).

To summarize where I have been so far, it appears to me that the rejection of realism is due partly to the failures of realism as a philosophical system (the loose ends and failures mentioned above) but also due to the difficulties that quantum mechanics presents when we try to think of the subatomic world from our scale chauvinistic view, both from the standpoint of how to visualize objects and the lack of causal connections to outcomes. Yet it seems that realist views of the theories have worked to produce many advances in science, even in the cases when the theories are later shown to not be correct. I want to now look at how I believe we should view such models.

7 The Grace of God in Science

I have always been struck by the fact that in physics we have theories about various phenomena that work extremely well, yet we know are incomplete descriptions. If we hold to the idea that all knowledge is revelation (Morris and Petcher, pp. 216-220) then even these "incorrect" theories are gifts from God. Let me explain my point by several examples.

First I look at Newton's laws, including his law of gravity. These are still used today in just about every engineering situation, space travel, etc. where speeds are not close to the speed of light or gravity is not very strong. Yet we know that Einstein's theories of relativity are better approximations to the nature of motion and gravity. However, applying Einstein's theories to most everyday situations would not be helpful since the difference between the two would be negligible. The amazing point to me is how useful Newton's laws, incorrect as they are, have been and continue to be. God did not just give us a model of gravity which worked well, say, for objects in the atmosphere of Earth, and then another that we could use to the Moon, and then another we could use out to Pluto. Newton's model works over an incredible range of distances, but it is not *True*.

Second, I would point to Maxwell's equations of electromagnetism. These again are used in nearly all communication systems, circuit designs, anywhere where radio, microwave, or light is used. Yet here also we know the theory is not complete. It cannot describe the interaction between say electrons and electromagnetism in all areas, and has been supplanted by Quantum Electrodynamics (QED).[17] QED however is a very difficult theory to use and would not be helpful in our day to day studies of radio waves. Maxwell's equations work extremely well over a vast range of frequencies (helping us to model radio, microwave, visible light, and ultraviolet radiation). God could have chosen to give us one set of equations for visible light, another for radio, etc. Instead he allowed us to have Maxwell's theory, which is an incredible theory but it again is not *True*.[18]

My last example of this is Schrödinger's theory of quantum mechanics, which I discussed above. Again, though this is a puzzling theory, we can work out the solutions to it in certain cases and it works very well (for example in calculating electron behavior in condensed matter physics) but it is known to not be accurate for the case of relativistic

[17] QED is the most accurately tested of the physical theories we have now, making successfully tested predictions on the electron to a level of approximately 1 part in 10^9.

[18] It is in Maxwell's theory I try to impress upon my students the issue of scale chauvinism, since we can only see an incredibly small component of the electromagnetic world out there through our sight. We are quick to baptize that view as normative when in reality it is such a paltry component of how the world should be viewed.

corrections. However, the use of those equations to study most atomic or condensed matter physics would not be warranted, since the corrections would not be relevant. Again, this theory is extremely accurate over a wide range of phenomena, but it is not *True*.

To me, what these examples speak about is God's incredible grace to us in the various science and engineering fields. These equations I have discussed work over a phenomenal range (Newton's law of gravity is very accurate out to solar system distances, as NASA can attest) allowing us to use them in our stewardship responsibilities, even though they are not the fully correct theories. Although this may give more weight to antirealist views, (since I am saying we are using equations that we know are not completely true yet have sufficient empirical accuracy) I cannot help but think that the fact we can still use science in incredible ways with incomplete theories is a picture of God's faithfulness to provide what we need at various times, yet then showing us the limitations of our knowledge to continue to humble us so we will not be arrogant in our knowledge. So to my view, the success of science is not due to realism, but instead is due to God's grace and mercy. I have to also wrestle with the fact that I see His enabling advances when we engage science with a realist viewpoint. With these thoughts in mind, I want to lay out a view of realism that I think can hold the tensions I have discussed.

8 Humble Realism

I want to first acknowledge that my attempts to bring philosophy in will likely be fraught with difficulties. Nonetheless, I want to fold all these issues together. As I have tried to state, it appears to me that only through a realist perspective can we achieve the empirical adequacy we need in our sciences. Even though oftentimes our views of the nonobservables in theories may be totally wrong, it is in the belief of the reality of these things that we seek new connections and by the grace of God find insights that would not have been reached otherwise. However, we must not view our theories as true in any complete sense, for they cannot be. In my first paper I had some initial thoughts about what I termed "Faithful" Realism. With the various perspectives I have discussed, it would seem to me to be far better to term my view Humble Realism for that must mark how I would hold the views of theories. Humble Realism does not accept the tenets of antirealism, in saying that theories have no connection to reality, nor would it accept a classical realist view that the objects must be consistent with our scale chauvinistic views or that if a theory is successful then it is *True*. Humble Realism would first of all see that the goal of science as glorifying God and enabling us to be better stewards of His creation. In order to do that, Humble Realism would see science as attempting to discover truth about the nature of reality, but is aware that a complete understanding of even a limited part of reality is going to be beyond us. The entities and laws postulated by theories are assumed to be accurate, yet incomplete, approximations to what is present in the theory-independent world, but the mental model of those images must be informed by the problems of scale chauvinism we all struggle with. Humble Realism embraces the view of humans as limited and fallen creatures, who realize that our finitude is a gift from God, all the time acknowledging that the truth of *Imago Dei* has something to do with how we can be stewards of this creation, including the ability to grasp a limited understanding of God's faithfulness in creation. Humble Realism acknowledges that past theories, although shown to be incomplete and false in some ways, can still be used as well as seeing that these theories do seem to arise from more accurate theories. Humble Realism cannot do a better job on quantifying verisimilitude than the many philosophers who have tried, but it can acknowledge that we often do distinguish between competing theories and can tell which does a better job. Humble Realism must take full ownership that the issues of confirmation cannot be fully solved, and as such can never claim absolute confidence in any theory, however, as a theory is more and more successful, we can have more confidence that it applies to reality in a limited manner. Humble Realism acknowledges that it is only because of a faithful God that one can understand some aspect of reality in a limited way and that all the knowledge we have is revelation from the one who holds all things together (Colossians 1:18) Finally, Humble Realism will hopefully allow one to take joy in what we learn about God's creation.

This issue of joy in our scientific pursuits is a very personal one to me in the midst of this discussion. Having studied physics for over 30 years, I have never ceased to find delight in the discoveries of science, even in areas outside my area of specialization. Whether the field is the latest research in elementary particle physics, ways to make concrete self-cleaning, or how cancer tumors emit chemicals to suppress new tumor growth, I am just thrilled to see what God allows us to learn. When I think of the answer to the first question in the Westminster catechism, to "glorify God and enjoy him forever," part of my enjoyment is in the sciences and the discoveries He allows. If I tried to do this with an antirealist hat on, I suppose I could thank God for the latest empirical adequacy, but I find it hard to imagine it. Viewing science through antirealist eyes would suck the joy out of my science.

9 Pedagogical Considerations

Having worked in research for over 13 years and taught for over 8 years, I want to turn my focus on how these issues can impact our students. When I think about teaching in the sciences, the first point I would make is that textbooks in science generally approach the field with a realist perspective. I have examined many physics texts and rarely do they talk about electrons, protons, or quarks as useful parts of a calculus for empirical adequacy. One counterexample would be a text I used in my education written in 1970. On the topic of quarks, which were just being proposed as an explanation for the great number of new particles created in accelerators, this text stated "One can believe either that the quarks correspond to actual particles or are simply a convenient way of seeing regularities in hadrons." (Ashby and Miller, p. 478) The authors of this text would not be seen as antirealist in their tendencies here, but merely reflecting the uncertainty of the time before the quark model had undergone much testing. This is clear from statements such as "Thus, we have the following particles, which are stable under strong and electromagnetic interactions: p, n, Λ, $\Sigma^{\pm}$, Ξ^{-}, Ξ^{o}, Ω^{-}, K^{+}, K^{o}, π^{+} and their corresponding antiparticles. These particles last long enough so that their path length is of reasonable size in a bubble chamber, and they can be detected by this means." (Ashby and Miller, p. 472) If they hold to the reality of these objects by the tracks they leave in bubble chambers, they are realists. As mentioned earlier, the view of the wavefunction in quantum mechanics as merely a calculational device is common in some texts,(Tipler and Llewellyn) yet in the rest of their presentation, the other nonobservables mentioned (quarks, neutrinos, etc.) are presented in what appears to be a realist manner. The fact that textbooks seem to follow a realist perspective could also be interpreted as Thomas Kuhn did, that once the paradigm has taken over, it rewrites the textbooks so as to justify the paradigm.(Kuhn, pp. 136-137) (Of course, this would undercut Fine's argument that the current paradigm is antirealist) With the advent of quantum mechanics and the struggles over determinism and causality, most textbooks have chosen to not deal with these issues, so I am not sure if a Kuhnian view holds in our present situation.

There is a larger issue to me than the matter of textbooks. I would invite the reader to imagine for a moment a biology course discussing the human genome project or designer DNA drugs and trying to motivate young students to pursue these fields purely on the basis of empirical adequacy. Do we train chemists to deal with polymers by ignoring the structures these nonobservables make and emphasizing just mixtures and temperatures? Will we inspire students to study God's creation with joy and passion from the call to improve our empirical adequacy? I simply cannot see it. From the standpoint of education, I could not be a teacher if I held to antirealism. (Which is why I struggle with the fact that Ernst Mach was an educator for many years). I cannot claim that to be a successful scientist or teacher of science one must be a realist, for that would be an arrogant claim.[19] I must approach education from the viewpoint that remembers the call of Humble Realism: We do not know all things and what we do know is a gift to us. Our present theories must be held in tension with our limited and fallen natures. So I must not be arrogant in my presentations of science. However, I can see from my perspective, to do what I do in a sense compels me to be a realist. It has been my time teaching at Covenant that has opened my eyes to these deeper issues.

10 Conclusion

In this work, I have looked at antirealist approaches to science and criticized them for how they look at science and how they fail to prepare us for doing or learning about science. I have given examples of how realism has lead to many advances in our understanding, and in my own field I have looked at how we can think about the entities proposed, especially the wavefunction in quantum mechanics and electrons. I have tried to lay out a view of realism that takes into account our struggles with our finitude and our attempts to limit the models we use to our scale as well as acknowledges the problems that realism has. One of the hallmarks of my view, Humble Realism, is that I must be humble in how I present it to my students, colleagues, and others. As my friend and colleague Don Petcher knows, this is the area I will struggle with most. My greatest desire for all that I interact with is to be filled with joy over what God has so graciously allowed us to see in His creation, and to give Him praise for His many blessings.

[19] Arrogance is well noted in physics as J. Murray Gibson discussed in his opinion piece "Arrogance–A Dangerous Weapon of the Physics Trade?", Physics Today, vol. 56, page 54 (2003).

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12 Bibliography

Anderson, P.W., "When the electron falls apart", Physics Today, vol. 50, 42-47 (1997).

Araki, T. *et al.*, "Experimental investigation of geologically produced antineutrinos with KamLAND", Nature, vol. 439, pp. 499-503 (2005).

Ashby, Neil and Stanley C. Miller, *Principles of Modern Physics*, (San Francisco: Holden-Day, Inc., 1970).

Ashworth, Jr, William B. "Catholicism and Early Modern Science" in *God and Nature: Historical Essays on the Encounter between Christianity and Science* ed. David C. Lindberg and Ronald L. Numbers (Berkeley: University of California Press, 1986)

Broussard, Phillip, "A Reformed View of Fictionalism and Antirealism in the Sciences", unpublished.

Broussard, P.R., S.B. Qadri, V.M. Browning, and V.C. Cestone, "Characterization of transport and magnetic properties in thin film $La_{0.67}(Ca_xSr_{1-x})_{0.33}MnO_3$ mixtures", Journal of Applied Physics, volume 85, pp. 6563-6566 (1999).

Chandrasekhar, V., M.J. Rooks, S. Wind, and D.E. Prober, "Observation of Aharonov-Bohm Electron Interference Effects with Periods h/e and $h/2e$ in Individual Micron-Size, Normal-Metal Rings", Physical Review Letters, vol. 55, pp. 1610-1613 (1985).

Fine, Arthur, "The Natural Ontological Attitude", in *Philosophy of Science* ed. Martin Curd and J.A. Cover (New York: W.W. Norton and Company, Inc., 1998), originally published in *Scientific Realism* ed. Jarrett Leplin (Berkeley: University of California Press, 1984), pp. 83-107.

Frauenfelder, Hans and Ernst M. Henley, *Subatomic Physics*, (Englewood Cliffs: Prentice Hall, 1974).

Greenstein, George and Arthur G. Zajonc, *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics* 2nd ed., (Sudburry: Jones and Bartlett Publishers, 2006).

Herbert, Nick, *Quantum Reality: Beyond the New Physics*, (New York: Anchor Books, 1987).

Hesse, Mary B., *Science and the Human Imagination*, (London: SCM Press, 1954).

Kuhn, Thomas S., *The Structure of Scientific Revolutions* 2nd ed., (Chicago: University of Chicago, 1970).

Laudan, Larry, “A Confutation of Convergent Realism”, in *Philosophy of Science* ed. Martin Curd and J.A. Cover (New York: W.W. Norton and Company, Inc., 1998), originally published in *Philosophy of Science* vol. 48, pp. 19-49 (1981)

Laudan, Larry, “The Demise of the Demarcation Problem”, in *But Is It Science?*, ed. Michael Ruse, Buffalo, N.Y.: Prometheus Books, 1988, 33750.

Lewis-Hall, M. Elizabeth and Erick Thoennes, “At Home in Our Bodies: Implications of the Incarnation for Embodiment and Christian Higher Education” in *Christian Scholar’s Review*, vol XXXVI, no. 1, Fall 2006.

Lindley, David, *Boltzmann’s Atom: The Great Debate that Launched a Revolution in Physics*, (New York: The Free Press, 2001)

Mascall, E.L., *Christian Theology and Natural Science*, (London: Longmans, Green and Co. Ltd, 1956).

Moreland, J.P., *Christianity and the Nature of Science: A Philosophical Investigation*, (Grand Rapids: Baker Book House, 1989).

Morris, Tim and Don Petcher, *Science and Grace* (Wheaton: Crossway Books, 2006).

O’Hara, T.C., P.R. Broussard and R.G. Goodrich, “Electron-phonon scattering rates in antimony: RFSE”, Journal of Physics F, volume 12, pp. 67-77 (1982).

Pais, Abraham, *Niels Bohr’s Times in Physics, Philosophy and Polity*, (Oxford: Clarendon Press, 1991).

Pais, Abraham, *Subtle is the Lord: The Science and the Life of Albert Einstein*, (Oxford: Clarendon Press, 1982).

Primack, Joel R. and Nancy Ellen Abrams, *The View from the Center of the Universe*, (New York: Riverhead Books, 2006)

Ratzsch, Del, *Science and its Limits*, (Downers Grove: Intervarsity Press, 2000)

Sproul, R.C. *Not a Chance: The Myth of Chance in Modern Science and Cosmology*, (Grand Rapids: Baker Books, 1994).

Tipler, Paul A. and Ralph A. Llewellyn, *Modern Physics* 4th edition, (New York: W.H. Freeman and Company, 2003).

Van Fraassen, Bas C., *The Scientific Image*, (Oxford: Oxford University Press, 1980).