Concepts of the Electron

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ABSTRACT. Experimental realism includes the philosophical position of Ian Hacking which attempts to explain how it is that experimentalists come to view fundamental particles as real. These discussions are frequently applied to the electron and the history of its discovery. The views of philosophers, historians, and scientists are considered in these discussions; however, the views of science students on the reality of electrons have not been discussed in the literature to a significant extent. This article argues that historical considerations which have a bearing on Hacking's position do not entirely support his view on experimental realism. During the period of the discovery of the electron, scientists tended to develop a realist view of the electron based on its measurable properties. A study of university-level physics students' written views about evidence for the reality of the electron reveals a strong similarity to views of the earlier scientists. I propose the use of historical materials to assist science students in developing a more thoughtful perspective on such issues.

1. Introduction

The term "electron", or one of its predecessors, began to emerge as one referring to a real entity from about 1871 with Varley's work on cathode rays. The work on cathode rays culminated with J. J. Thompson being credited with having "discovered" the electron in 1897. Yet, as late as 1906 Philipp Lenard still denied the materiality of electrons in his Nobel acceptance speech. On the other hand, when Arthur Eddington suggested to Ernest Rutherford that electrons might only be concepts rather than have real physical existence, Rutherford replied, "Not exist, not exist?—why I can see the little beggars there in front of me as plainly as I can see that spoon" (Dyson, 1988, p. 43).

Commenting on such episodes in the history of the sciences, philosopher Ian Hacking claims that in most experimental sciences, there is a time when experimentally-manipulated entities become "real" for the scientists. For Hacking the term "electron" began to "refer" when a scientist friend described the experimental process of changing the charge of niobium balls with an electron beam as "spraying electrons." Hacking writes: "So far as I'm concerned, if you can spray them then they are real" (Hacking, 1983, p. 23). The perspective of scientists and philosophers of science on the reality of fundamental particles is much discussed in the literature, but the views and beliefs of science students on the matter is an open question. Science students are known to hold some preconceptions about science similar to those of early scientists (Clement, 1982; Gauld, 1998; McClosky & Kargon, 1988). One could, therefore, speculate that science students and scientists have some common elements in their beliefs, say, about the electron. In addition to Hacking's view, this paper begins to explore the similarity of science students' and scientists' views on the reality of the electron.

2. Experimental Realism

Ian Hacking expounded his philosophy of experimental realism in 1983 in his widely-read book *Representing and Intervening*. Hacking agrees with philosophers, typified by Bas Van Fraassen, that realism in reference to theories is difficult to defend; however, he makes a distinction between realism in reference to theories and realism in reference to entities. Entity realism is, to Hacking, both natural and defensible for experimental scientists. The kind of entity realism that

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Hacking espouses is a causal theory, rather than a material theory of realism. A causal theory of realism is justified on the basis of effects that entities can produce and not on the basis of so-called material properties. Hacking justifies his entity realism on two grounds: first, real entities can be observed to have the same properties by independent methods of observation, and, secondly, real entities can be manipulated by experimenters to produce other unrelated phenomena. Hacking insists that theories about entities themselves do not play any significant role in the experimental manipulation of the entities.

Hacking's position has been criticized primarily on two points. First, critics maintain that Hacking fails to explain satisfactorily how experimentalists are able to demonstrate successfully various properties of entities and how they are able to produce various phenomena using those entities. By explaining these successes, Hacking's critics claim, he is engaging in a form of "inference to the best explanation," a justification strategy that is considered by many as an unwarranted justification for realism. Secondly, critics challenge the view that theory does not play any significant role in most experimentation where entities are used to produce phenomena. Hacking's version of experimental realism is challenged, both by using examples from the history of science and by using the argument of the theory-ladenness of all observation. Hacking's critics have, however, largely failed to point out that the process of validation of experimental entities takes time, that it may be the subject of debate, especially as it relates to the status of background theories, and that it generally contains subjective elements. These additional factors challenge the position that the acceptance of entities as real is a purely rational endeavour, something that is a necessary requirement for the defensibility of entity realism.

2.1 HACKING'S POSITION

Hacking observes, rightly so, that both realists and anti-realists have, up to this point, been primarily concerned with realism (or anti-realism) as it applies to theories of science. He states that "most of today's debate about scientific realism is couched in terms of theory, representation, and truth" (Hacking, 1983, p. 31). Van Fraassen, for instance, is opposed to claims of the inference of truth from theories or the existence of the entities postulated by those theories. To begin with, Van Fraassen insists that our knowledge and justified beliefs are confined to statements about entities and theories that are entirely in the macroscopically observable realm, that is, those entities that can be accessed directly by means of human senses (van Fraassen, 1998). In this regard, Van Fraassen borrows liberally from Aristotle's notion, as stated by medieval scholars: *nihil in intellectu quod non prius in sensu*—"There is nothing in the mind except what has passed through the senses." Therefore, according to Van Fraassen, any data about theories or entities that we obtain indirectly by means of instrumentation result in an underdetermination of the theory by such evidence, since the data did not directly move from the source to our senses. The underdetermination results from our inability to say for certain that another theory or another entity or mechanism could not equally well have produced the data.

Hacking agrees with Van Fraassen that all theories are underdetermined and he clearly separates issues about theories from those about entities. About representational realism, Hacking says that "there can be no final argument for or against realism at the level of representation" (Hacking, 1983, p. 31) and he refrains from debate on that issue. On the other hand, Hacking argues that underdetermination does not hold for realism about entities in the domain of experimentation. In order to support this view, Hacking puts forth a causal definition of what it means to be "real" for an experimental entity. Hacking says that "we shall count as real what we can use to intervene in the world to affect something else, or what the world can use to affect us" (Hacking, 1983, p. 146). Resnick interprets Hacking as saying "real entities can causally interact with the world; unreal ones cannot" (1998, p. 1170). But Van Fraassen creates a problem for Hacking's position when he claims that the only observations about which one can make valid knowledge claims are those that can, potentially, be made directly with human senses. In response, Hacking argues that human senses can be extended by instruments in order to make knowledge claims about observations indirectly made with instruments; for instance, an optical microscope and an electron microscope could be used to observe the same entities, yielding the same features. These instruments are independent in the manner that they function and produce their measurements; hence, the observer can infer that the entity is real. As pointed out by Reiner and Pierson (1995), Hacking has reserved his argument for tiny but, *in principle*, observable entities. Hacking sidesteps challenges by not using the extensibility-of-observation argument for entities that are, in principle, unobservable, like electrons. I have reconstructed the arguments for realism when using instruments in the following manner:

1. We should take instrumental observations to be true about entity E if and only if instrument A and instrument B produce the same observation, O, and instrument A and instrument B are independent of each other.
2. We make the same observation, O, about the entity E with instrument A and B.
3. Therefore, we are justified in considering observations about E to be true.

The argument can be illustrated by a simple example. In solid state physics there are certain crystals with defects called "colour centers" (E). The colour centers can be "observed" by means of a spectrophotometer (A) that shows absorption peaks (O) where certain colours are absorbed by the defects. By a completely unrelated method, positrons are injected into the crystal (B) where they are trapped by the colour centers. Positrons so trapped exhibit an anomalously long lifetime (O), since the amount of overlap of their wavefunctions with those of the electrons of the crystalline atoms is much less inside the defects. The observations (O) produced by (A) and (B), while not identical, each in their own way illustrate the existence of entity, E. Another, more famous example, taken from Abraham Pais's biography of Einstein (Pais, 1982), is the remarkable series of at least twelve diverse and unrelated determinations of Avogadro's number by 1909, which served, for many, as conclusive evidence for the existence of molecules and the concept of atomism. The experiments used to determine Avogadro's number included Brownian motion, blackbody radiation, Rayleigh scattering, alpha-scattering, and Bragg crystal scattering.

Reiner and Pierson (1995) argue that Hacking's justification depends on the fact that A and B produce the same result and on the coincidence that would need to be explained, were these results not from the same cause. Reiner and Pierson's re-statement of Hacking's argument is a form of "inference to the best explanation" (IBE). The issue with attributing IBE to Hacking's position is not that his position is fatally weakened (since arguments can be made that the circularity inherent in IBE is not a fatal flaw) but that it contradicts his strong denial that his argument is, in fact, employing IBE.

Hacking's second and main argument for entity realism is that experimental entities can be causally manipulated. He states that "experimenting on an entity does not commit you to believing that it exists. Only manipulating an entity, in order to experiment on something else, need do that" (1983, p. 263). Hacking's argument rests on the premise that if the experimenter causes a phenomenon using the experimental entity, then the entity is real. The act of intervention is seen as a causal process. Resnick summarizes Hacking's argument as follows:

1. We are entitled to believe that a theoretical entity is real if and only if we can use that entity to do things to the world.
2. We can use some theoretical entities, e.g., electrons, to do things to the world, e.g., change the charges of niobium balls.
3. Hence, we are entitled to believe that some theoretical entities, e.g., electrons, are real (Resnick, 1998, p. 1175).

Resnick points out that it "would be an incredible coincidence if we managed to use an entity as a tool for inquiry that did not, in fact, exist" (1998, p. 1178). Resnick's observation makes it obvious that Hacking's second argument is, like the first, open to the charge that it is really a case of inference to the best explanation.

3. The *Process* of Becoming a Real Entity

Hacking's experimental entities "become real" (Hacking, 1998) when the scientist-experimenter is finally able to "manipulate the entity in order to experiment on something else" (Hacking, 1998). Does the entity literally "become real" or is the entity only discovered to have been real all along? Reiner and Pierson (1995) point out that Hacking's picture of scientific practice yields the realist conclusion about the electron as an automatic matter of course, not as the result of a developmental process of evidence-gathering, so that, strictly speaking, the entity is discovered as having been real all along. However, to the experimentalist the progression is one of gradual unveiling and the term "becoming real" is a psychological term describing what goes on in the experimenter's mind. "Becoming real" is a process—it takes time and relies on scientific judgment. Metaphorically, the process is somewhat like "becoming a real boy" in the Pinocchio story (Collodi, 1946/1883). When Pinocchio proved he was "good" enough and could work hard, rather than playing, he was granted the wish of becoming a real boy. Methaphorically, Hacking's brand of experimental realism is a "Pinocchio" realism. When the postulated entities stop being playthings and do real work for the scientist, they are worthy of becoming real.

By implication, the process of "becoming real" is not sudden, and it is not completely straightforward. The process of validation, then, may not be completely rational—subjective considerations such as strong attachment to certain theories and interpretations of data may play a role. However, Hacking claims that scientists "know" when entities are real. Knowing is usually defined as "justified belief". In other words, knowing, in this sense, is rational.

3.1 THE ELECTRON BECOMES REAL

I will briefly consider one of Hacking's favourite examples, that of the electron. How did the notion of "electron" evolve? Initially, the entities later called "electrons" were seen as cathode rays. Cromwell Varley, in his paper "on the Discharge of Electricity through Rarefied Media" (1871), was the first to propose that these luminous discharges are composed of "attenuated particles of matter" (p. 239), negatively charged. Varley was able to bend the beam by using a magnetic field produced by a coil, as had Julius Plücker before him. Varley further demonstrated the ability of the beam to deflect a suspended object physically. Varley's work anticipated the much later investigations of J. J. Thompson. Then, in 1874, Johnston Stoney estimated the "minimum quantity of electricity" to be 10^{-20} coulomb, and later, in 1891, he was likely the first to use the term "electron" for the electrical charge involved in the chemical bond. However, it was not obvious to everyone that the electron of chemistry was the same entity as the electrical charge of cathode rays. In 1897, J. J. Thomson supported the initial contention of Varley that cathode rays were particles which he now termed “carriers of the electricity” or “corpuscles” (Thomson, 1897, p. 295), and he speculated that the mass was about 1000 times smaller than that of a hydrogen atom. Thomson was later awarded the Nobel Prize for this work. Initially, the scientific community was not convinced about Thomson’s claims. Thomson recalled, much later, that

> [at] first there were very few who believed in the existence of these bodies smaller than atoms. I was even told long afterwards by a distinguished physicist who had been present at my [1897] lecture at the Royal Institution that he thought I had been ‘pulling their legs’ (Thomson, 1936, p.341).

Thomson used the generic term “corpuscles” until after 1906 (Smith, 2001).

One reason for the general hesitancy to accept the electron was the reluctance of many to accept the notion of atomism. The luminiferous ether of Maxwell and Lorentz had made it possible to work out theories in which particles (atoms) were simply vortex disturbances in the ether. Realism for fundamental particles was not universally accepted. As late as 1902, Kelvin published a paper in which he proposed that the electrical fluid of Aepinus, which was based on Franklin’s work, was, in fact, composed of “electrions,” that were merely vortex-like disturbances in the ether. In his Nobel lecture of 1906, Philipp Lenard categorically denied the materiality of cathode rays stating that “we have no evidence that (negative) electricity is a special *material* with inertia” (1906, p. 119, italics in original), describing them, rather, as “waves in the ether” (p. 114) or “pure ether phenomena” (p. 119). Apparently, at that time atomism was still a subject worthy of debate. Atomism was likely not universally accepted until after Einstein’s paper on Brownian motion in 1905 and possibly not until Rutherford’s work on the atomic nucleus in 1911. The remarkable story of the discovery of the massive atomic nucleus illustrates how revolutionary the new atomic concept was, at the time. What led up to Rutherford’s planetary model of the atom was partly the work of his associates Geiger and Marsden, in 1909. Geiger, needing to find a job for Marsden to do, had asked Marsden, at Rutherford’s suggestion, to see whether alpha particles would be deflected through very large angles from a thin gold foil. A few days later, the news came back to Rutherford that some alpha particles had, in fact, been deflected backward. Rutherford was greatly excited by this news as he recounted later. In his words, “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you” (quoted in Heilbron, 1964, p. 236). The same year as the astonishing discovery of the atomic nucleus—1909—Millikan reported his initial measurements of the fundamental electrical charge, which he identified with the electron at the Winnipeg meeting of the British Association. Millikan spoke only after Rutherford had noted that “it has not yet been possible to detect a single electron by its electrical or optical effect and thus count the number directly, as in the case of alpha particles” (quoted in Fletcher, 1982, p. 45). Rutherford’s observation is telling of the undercurrent of uncertainty that accompanied the electron, even as late as 1909. When Millikan accepted his 1923 Nobel Prize in Physics, he recalled that after the 1897 work of Thompson, “there remained, however, some doubters, even among those of scientific credentials, for at least two decades” about the reality of the electron (Millikan, 1924, p. 55). So, if one pinpoints the work of Varley in 1871 as the first indication of the elementary and material nature of the electron, one can legitimately argue that the emergence of electrons as “real” took approximately 40 years. John Heilbron has argued for a slightly shorter period, stating that “from 1902 the physicist was … justified experimentally in considering the corpuscle a free atom of electricity, a disembodied electron, and he generally so regarded it” (1964, p. 98).

But, let us revisit the discovery period for the electron and see what experimental properties were known about the electron even before its mass and charge were accurately established by various methods. Already by 1880 it was established that cathode rays "are emitted normal to the surface of the cathode, that an object placed in their path casts a sharp shadow, and that their trajectories, though bent by a magnetic field, are apparently unaffected by an electrostatic force" (Heilbron, 1964, p. 60), and that they are carriers of a significant amount of momentum (Varley, 1871). It was experimentally obvious almost from the start that cathode rays carried negative charge, although Perrin was the first to prove it, systematically. During that period it was also demonstrated that cathode rays cause some substances to emit a phosphorescent glow and that they can heat a target. These early-established laboratory properties are reminiscent of the restatement of Hacking's realism by Resnick: "We are entitled to believe that a theoretical entity is real if and only if we can use that entity to do things to the world" (p. 1175). It is obvious that causing a small wheel to rotate or causing a small target to become red hot is "doing things to the world". However, scientists were doing those things long before the material properties, such as mass and charge, were well-established.

The above historical sketch suggests that scientists were only convinced as to the reality of electrons by the determination of material properties, such as mass and charge, and by the change in their view of atomism, brought about by factors such as the discovery of the nucleus. In other words, if the laboratory properties of an entity are not well established before it is used to produce other phenomena, then it is not accepted as real. In addition, if the scientific intellectual climate is not appropriate for acceptance of the entity, this can also have a bearing on its acceptance. In the case of the electron, the determination of physical properties, such as mass and charge, by diverse experiments seems to have been the deciding factor, and not the ability to "spray" electrons in the form of a beam, something scientists could do long before with their cathode ray tubes.

4. Implications for Hacking's Entity Realism

Hacking's first picture of entity realism extends sensory observation to instrumental observation. Such observations can be as valid as direct sensory determination, according to Hacking's argument outlined above. However, Hacking does not intend this argument to be used for validation of entities that are unobservable, in principle. He makes this clear when he says, when referring to electrons, "experimenting on an entity does not commit you to believing that it exists" (Hacking, 1983, p. 263). Thus, determining the physical attributes of an entity by diverse methods, as was done for the electron in the sketch above, would not count as validation. The fact that Hacking does not allow for validation through determination of physical attributes in the case of entities such as electrons does not appear to match with the history of science. Validation of entities such as the electron is conventionally affected by factors other than the deliberate use of these entities as tools to produce other phenomena. Other factors such as validation of physical properties and beliefs about the world play a major role.

Hacking's picture of entity realism would be strengthened were he to accept an additional means of experimental validation of entities that are, in principle, unobservable. This validation operates by the determination of physical properties of the entity by diverse methods. Furthermore, in any case of the validation of entities, one must account for the presence of outside factors that relate to beliefs about theories, philosophical positions, and even subjective attachment to certain interpretations of data. This last issue challenges the claim that experimental entities can necessarily be objectively validated. Reiner and Pierson propose a fallback position for Hacking’s realism, which, in their opinion, would be much more defensible. They propose that all we can deduce from experiment is the existence of “experimenter’s entities” (Reiner & Pierson, 1995). This would, however, fly in the face of Hacking’s main objective, which is to justify the realism of experimental scientists. For Hacking, the main point is that experimental entities go beyond being curiosities—they can be used to do work for the experimenter. They, like the puppet Pinocchio in Collodi’s fairytale, move from the state of merely being postulated to being validated as real. Hence, Hacking’s picture could be described as the Pinocchio picture of entities.

My purpose in commenting on Hacking’s position is not, primarily, to enter the debate on experimental realism, but to move the discussion beyond philosophical consideration and historical application to the current experience of science students. Let us now turn the discussion to the views of science students on the realism of the electron. How does it compare to the views expressed by philosophers of science and how does it compare to the historical record?

5. Implications for Science Education

There is a recurring discussion in the science education literature as to whether students, to a significant degree, reflect historical scientific views in their own preconceptions about science (Clement, 1982; Kuhn, 1977; Nersessian, 1989; Piaget & Garcia, 1989; Schecker, 1992). It is beyond the scope of this paper to consider the arguments for and against the preconception-history correspondence. For the purposes of this discussion, it is simply assumed that naïve student preconceptions are *sometimes* similar to those of early scientists but that students do not necessarily develop in their thinking the way that science developed historically. Against this background and that of the discussions about experimental realism and history of science, I will now raise some pertinent questions about science students and their justified beliefs. My questions follow in the tradition begun by Arnold Arons who posed the questions “*How* do we know …?” “*Why* do we believe …?” “*What* is the evidence for …?” of his students (Arons, 1973, p. 771, italics in original). A typical “Arons question” was “What is the evidence that [the electron] is a universal constituent of matter?” (1973, p. 774).

If students were to express their beliefs about the reality of electrons and the reasons for those beliefs, would their reasons be anything like “Pinocchio” realism or, alternatively, realism based on consistent and diversely-measurable laboratory properties? Beyond the issue of student beliefs about the electron, there is the issue of depth or adequacy of understanding on the students’ part. Do students have *any* thought-out beliefs about electrons, and if so, can they provide adequate reasons for their beliefs? It has been established some time ago in the literature that science students have difficulty giving clearly-conceptualized reasons for various beliefs that they may hold in the domain of science (Arons, 1973; Lederman & O’Mally, 1990; Stinner, 1992). This phenomenon is present from the beginning of students’ study of the sciences and even through their university years (Peters, 1982). It is always both interesting and rewarding to take questions such as these and move beyond speculation to a controlled research study. Not only can information be sought on which side of the realism debate science students fit, but such knowledge can also provide guidance for improving the teaching and learning of science issues and concepts. To that end, a research study was designed and carried out and this is described, below.

5.1 THE RESEARCH STUDY

To establish the feasibility of the research study, I first identified the potential test population. The subjects should be advanced enough in their science knowledge to have the resources to answer questions about the electron. Also, significant instructional resources should be available for future intervention in other studies designed to test instructional effectiveness. The ideal group was deemed to be a second-year physics laboratory class (N=25) where several experiments involving the electron are already included. The class had already performed experiments replicating Thomson's determination of the charge to mass ratio of the electron and Millikan's work on the elementary electronic charge. These two experiments had been presented, largely, in a traditional manner, but some historical background was included. Students had not been asked to consider the issue of realism for the electron. The study was carried out during the final class of the course, when students would be expected to have accumulated sufficient background knowledge to answer questions about the electron. Students were not given any indication ahead of time that the questionnaire would be administered.

Two research hypotheses were formulated, namely, (a) students tend to be realists about the electron and (b) students tend not to have a clearly-developed view on the ontological status of the electron. The test of the hypotheses took the form of a simple questionnaire with students participating, anonymously. The questionnaire can be answered in about five minutes (see Appendix). In order to guarantee both explicit student agreement to participate in the study and their complete anonymity, the answering of the questionnaire comprised the student's agreement to participate.

5.2 RESULTS

Of the 25 students eligible to respond, one was absent and sixteen elected to respond to the questionnaire. Of the 16 responses, 10 were realist, one instrumentalist, and two "agnostic". The remaining responses were judged to be inadequate to be considered as a statement of support for the position taken. In order to be considered adequate on the realist side, at least two measurable properties had to be listed.

The Realist Position. Seven of the realists listed measurable properties as the main evidence. For example, one respondent wrote: "The electron is real in that it displays consistent and measurable properties." Another wrote: "I like to compare the qualities of the electron to other things that I believe are real. For me, if something is real then it will have certain qualities (but not limited to) such as mass, charge, and energy." Two realists used a "miracle" type argument— "there are known properties that could not be explained without it". Lastly, one realist used a Hacking type argument: "it can be used in applications such as the e-microscope".

The "Agnostic" Position. Two respondents were not prepared to take a position on realism, citing the wave-particle duality of the electron as a reason.

The Instrumentalist Position. One respondent took an instrumentalist position, writing that the electron is "designed to simplify physicists' understanding of the universe".

5.3 DISCUSSION

One wonders if the students who opted not to respond (8 out of 24) did not do so because they had no opinion, or they had an inadequate understanding of the question, or they simply could not be bothered to put forth the effort. Several of the responses were expressed well and clearly thought out. The remainder were weaker, reflecting the likelihood that the students had not thought about the issue before.

It should be remembered that the subjects of this investigation had all received instruction that did not refer to ontological issues relating to the electron and did not use history of science in a pervasive manner during instruction. They had not been asked to consider realism about the electron before, unless the issue had arisen outside the course. Most of the students clearly took a realist position, bearing out hypothesis (a). It is interesting to note that only one student expressed the view of "Pinocchio" realism. One would not expect a significant number of students to express Hacking's brand of experimental realism if one assumes that the earlier conclusions about entity realism are correct. In other words, students reflect the fact that most experimentalists come to accept the electron as real when they have established "consistent and measurable properties", to quote an anonymous respondent.

The arguments given in defence of realism were, for the most part, not sophisticated. Some simply pointed out that a negative electrical charge and a mass are associated with the electron. These two facts cited by the students are ones they easily gathered from experiments that they had performed to measure the charge to mass ratio of the electron and the charge of the electron. The general lack of thoughtful elaboration or the lack of sophisticated reasoning support hypothesis (b).

6. Recommendations

Students often find experiments in physics to be, at the best, challenging, and, at the worst, confusing. They see experimental work from a completely different standpoint than the teacher or researcher. From the students' perspectives, the goals are primarily to follow sometimes meaningless instructions and to get the "right" answers (Hodson, 1993; Lunetta, 1998; Petrosino, 1998). The laboratory presents a daunting set of tasks for the student, the purposes for which are not at all clear in her or his mind. In the typical laboratory, the student must (a) understand the nature of the problem, (b) understand the procedure, (c) develop a theoretical perspective, (d) read, comprehend, and follow directions, (e) insure that they are getting along with their partner, (f) operate the apparatus and collect data, and (g) interpret results and write a report (Hodson, 1993). Hodson's concerns would certainly apply to physics experiments involving the electron. It is, therefore, not surprising that students do not form a well thought-out understanding about the electron.

Another factor that will have a bearing is student confusion about what the "theory" is for a particular experiment. Traditionally, the "theory" for a student laboratory measurement is the theory of the measurement technique, not the underlying theory that motivated the experiment in the first place. For example, in doing the Millikan oil-drop experiment, students are normally told that the theory has to do with applying Newton's Second Law and Stokes Law to an oil droplet. They are not, however, encouraged to think about what evidence is provided by their measurements for the existence of an *elementary* electronic charge and whether this charge is necessarily identical with the electron of the atom, electricity, and chemistry. Student understanding of background theory is an important concern if we accept that what counts as experimental fact must agree with the theory choice or background theory.

In order to provide a meaningful background for the underlying considerations about the electron, the most productive approach is likely to include an in-depth discussion of the issues debated by historical figures like Varley, Lenard, J. J. Thomson, Millikan, and others. Students would need to be introduced to theories of matter so they could come to appreciate the enormous complexity underlying the seemingly simple measurements of the charge to mass ratio and the electronic charge. To be complete, the additional complications introduced by quantum theory must also be considered. These issues, like the wave-particle duality, begin to be raised by experiments like electron diffraction—an experiment easily accessible in the student laboratory.

The task, then, is to re-design student experiments so as to provide a rich and an in-depth historical context and to clarify the distinction between the theory of the experimental method and the underlying theory of the experiment. One should not, however, expect that including history of science alone will produce better understanding (Abd-El-Khalick & Lederman, 2000)—students must be guided by well-designed questions in order to learn the required concepts. All this must be done in a manner to engage students and encourage them to participate in a significant learning opportunity. Current research and scholarship has much to say on this subject (Matthews, 1994; Stinner, et. al., 2003, Allchin, 1999; Klassen, 2005). The re-design process would involve not only one laboratory experiment, but a complete series of student experiments relating to the electron. The objective of doing so would be to cultivate well thought-out student concepts relating to the electron and about the science processes that brought about our current understanding.

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Appendix: Questionnaire

The Electron

Anonymous questionnaire

You may begin after your instructor leaves the classroom

Remember that there are no right or wrong answers and not being able to answer to your satisfaction is also useful information

After completing, please fold and put into the box provided

I believe that the electron ☐ is real
☐ is an invention of scientists' imagination
☐ other

Please explain your answer below: