What is electric current? : an investigation of student difficulties with the ontology of electric current
by Thomas Richmond Brown

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
In this dissertation, I describe a research project conducted at Montana State University aimed at enriching understanding of student difficulties with the subject of electric current. Toward this end, I adopted a model of conceptual change described by Michelene Chi in her work entitled, "Conceptual Change Within and Across Ontological Categories: Examples from Learning and Discovery in Science". The centerpiece to this model is the notion that student difficulties with the ontology of a new concept can impede their progress in the classroom. The goals of my research were (1) determining the degree to which errors in ontology are a problem for students studying electric current, (2) discerning specific difficulties that arise from those errors, (3) determining the degree to which existing instructional techniques and curricular materials at Montana State University are effective in addressing those difficulties, and (4) developing new curricular materials to specifically target difficulties stemming from ontological errors.

In pursuit of these research goals, data were gathered from students through individual interviews and through a questionnaire style instrument. The questionnaire was developed using the insight gained in the interview conversations. Analysis of student responses to the questionnaire items reveals that introductory physics students at Montana State University are extremely disposed toward ontological errors in their treatment of electric current. The data gathered from administering the questionnaire to students both prior to and after instruction provided much insight into the specific difficulties that stem from these errors in ontology. Employing the questionnaire in several different instructional environments revealed which strategies and curricular styles were more successful in addressing these difficulties. These data informed the development of new curricular materials. The assessment of the new materials revealed improved efficacy in addressing the specific student difficulties targeted in this study.

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ABSTRACT

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CHAPTER 1

INTRODUCTION

As physics instructors, we are quite accustomed to hearing incorrect responses to our questions. As physics education researchers, we have learned that many times an incorrect response is much more interesting than a correct one. A student who provides an incorrect response gives us a glimpse of the particular difficulties that the subject at hand is experiencing. It is from knowledge of what students do not understand that we gain the insight necessary to improve instruction. It is a rich, but incorrect response from a student that led me to the work discussed here, and it is worthwhile to relate the story as a prelude to the dialogue below.

The following conversation takes place between a non-science degree-seeking student and myself (the instructor) in an interactive classroom driven by the Physics by Inquiry (McDermott, Shaffer, and Rosenquist, 1996) texts. For those not familiar with these materials, the format of this curriculum is extremely effective in engaging students in meaningful classroom discussions. The classroom environment is commonly referred to as a "tutorial" style. Physics by Inquiry provides a set of activities and questions that students work through and discuss in small groups of three or four peers. The students very much guide the pace of the course and explore whatever tangents they wish, mostly within the boundaries of the curriculum! Almost no time is spent with the instructor talking at a blackboard in front of the class. Instead, the instructor assumes the role of a guide: allowing the students to freely explore, while discreetly steering their learning through a Socratic dialogue.

Our conversation starts as a group of students I had been eavesdropping on began examining two simple circuits. The first circuit consists of a battery and a single light bulb; the second circuit contains two bulbs connected in series. Their discussion prompted a question from me, which in turn began a discussion between me, and one student in the group. The following is a synopsis of the dialogue.

I: So would you say there is more or less current in this circuit? (referring to the diagram of the two bulb circuit and asking for a comparison to the one bulb circuit)

S: It's the same.

I: What about the brightness of the bulbs, are they the same?

S: Well no, the current is the same amount though.

It should be noted that at this point I was quite mystified by these statements and my mind was working furiously in an effort to understand this student's statements. She had already been asked to consider bulb brightness as an indicator of electric current: On what was this student basing this claim of equality?

I: So, did the addition of the second bulb change anything?

S: Yes, the current is the same, but it is moving more slowly. Is that wrong?

It is clear that what this student thinks of as electric current differs from the definitions held by the instructor. The commonly accepted definition of electric current would indicate a decrease in the current due to a "slower" flow: The current would change. However, this student's statements are far from nonsense. They can be interpreted quite effectively using a theory of cognitive structure and conceptual change proposed by M. Chi (1992). I'll ask that the reader consider the student's last statement carefully as I'll return to it in the pages that follow to illustrate the dangers that can be avoided by simply being aware of Chi's work.

CHAPTER 2

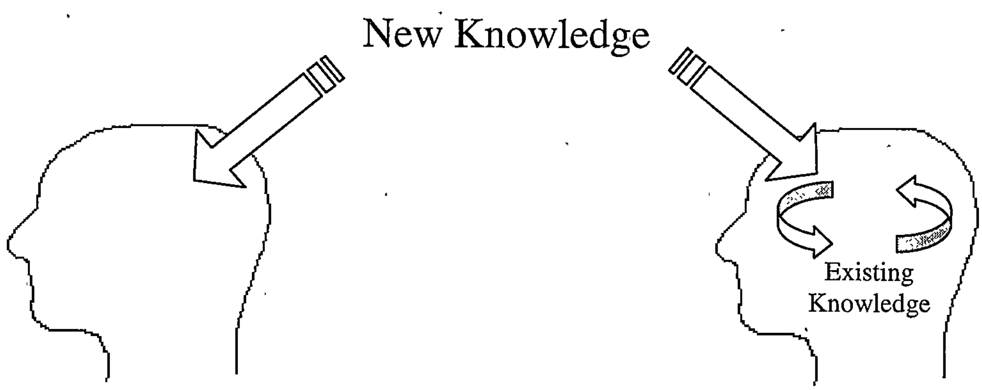
A THEORY OF CONCEPTUAL CHANGE

It should be noted that the purpose of this work is not to prove the suitability of one theory of cognitive structure or conceptual change over any other. Rather, it is my intent to apply one such theory to the study of student understanding in the context of electric current and illustrate its usefulness in both interpreting student learning (and response) and in informing curriculum development and instruction within this context. The concept of ontological category assignment, as described by Chi (1992), is the centerpiece to a lens through which I will view student learning throughout this work. In this section, I will discuss the nature of ontological categories, as well as the problems that arise when a student subconsciously assigns a concept to an incorrect category.

The Constructivist Viewpoint

The cognitive theory known as constructivism, which has its roots in the research of Jean Piaget, is central to the understanding of ontological categories and why they are an important influence on how students learn. The modern view of constructivism was shaped in the late nineteen seventies, largely through the work of Novak (1977) and Driver & Easley (1978). I will begin by contrasting two models of student learning and human thought. Prior to Piaget's influence, the process by which students learned a new piece of knowledge was viewed as similar to the way in which one might fill a pitcher with water. The learner is a passive blank slate, a willing receptacle waiting for the instructor to provide information. The student then learns this information as the lecturer disseminates it. The quality of the teacher's explanation governs the efficacy of instruction. Ausubel, Novak, & Henesian (1978) pointed out that the learner is not a blank slate, and has opinions and ideas that will be used to interpret the new knowledge. The difference between constructivist learning theory and its predecessors is crudely depicted in the figure below.

Figure 1. Two Learning Theories



The learner on the left demonstrates the empty vessel philosophy, while on the right we have a depiction of a more constructivist theory of learning. It is important to note that the theory exhibited by the student on the left does not suggest that the learner is not thinking about what goes in, nor does it suggest that there is no knowledge in the students mind! Rather it is an opinion that the knowledge already possessed by the learner is not interacting with the knowledge disseminated by the lecturer. If the student does know some physics, that knowledge is not actively being used to interpret the new knowledge. This is not meant to suggest that an instructor employing this model does not believe that prerequisite knowledge is useful or even necessary if the student is to understand the new topic. It would be ridiculous to try to teach a group of students who had never been exposed to calculus to effectively use Gauss' Law. The implication made by this learning model is that fostering an understanding of Gauss' Law and fostering an understanding of the calculus used in expressing and employing Gauss' Law are distinct problems. The belief is that one problem can effectively be addressed without attention to the other. Therefore, although it is important that students understand calculus, there is no need to specifically address how calculus is being used in the context of Gauss' Law as part of an understanding of what Gauss' Law has to say about the relationship between electric fields and charge distributions. If a student knows the relevant mathematics, then there should be no obstacle. This is the model most of us employ, whether we realize it or not, when we design our lectures.

The student on the right side of Figure 1 is actively, but subconsciously, using previous knowledge to help interpret and understand the new concept. An instructor employing this model of learning believes that addressing how this previous knowledge relates to the new knowledge is crucial. The constructivist viewpoint implies that even if a student understands the necessary mathematics, difficulties related to the requisite math may be encountered as the student attempts to integrate his or her calculus knowledge with an understanding of Gauss' Law. In other words, comprehension of calculus that exists independently from Gauss' Law is not a guarantee that calculus within the context of Gauss' Law will be understood. Furthermore, mastery of the relevant physics embodied in Gauss' Law will be dramatically impeded by difficulties encountered with the mathematics. Because the student is actively using what he or she has learned within each regime to interpret concepts within the other, understanding within the two regimes is seen as inextricably linked. In addition, the knowledge used in this process does not fall exclusively within physics or mathematics. In fact, it is likely that this represents only a small fraction of the knowledge being employed if the student in question is a novice in an introductory course. A wide range of previous experiences and ideas are being employed in an effort to fit a new physics concept into what is referred to as the student's existing cognitive structure.

To further clarify the differences between these two models of learning, it is useful to introduce some new vocabulary. Piaget (1964) devised a process by which new information is incorporated into the learner's existing cognitive structure that is commonly referred to as the "assimilation and accommodation" scheme. It is outlined in the steps below.

1. Assimilation: The process of incorporating new knowledge into the existing cognitive structure.
2. Accommodation: The restructuring of the existing cognitive framework to accommodate the new knowledge.
3. Equilibration: The new knowledge is now an integral part of a forever-altered cognitive structure.

This scheme should probably not be viewed as a sequential list, but rather as a cyclic process. Assimilation starts the wheels turning, but the accommodation that must take place changes the way in which the new knowledge is being assimilated, which then a new accommodation. All of this is, of course, seen as a subconscious exercise performed by the learner. Equilibration is what Piaget termed the conclusion of the assimilation and accommodation process. The learner has successfully integrated the new piece of knowledge and his or her existing cognitive structure into a new framework that includes the new concept or idea.

It is important to note that, according to constructivist theory, the new knowledge does not exist unchanged in the learner's new cognitive framework. Through the process of accommodation the learner augmented both his or her existing framework, *and* the new knowledge to be assimilated. In terms of the illustrative example I used above, both calculus knowledge and physics knowledge are augmented as the learner attempts to incorporate Gauss' Law.into an existing framework. The empty vessel model does not allow for prior knowledge to undergo changes as new things are learned: nor does it allow for the new knowledge to be augmented to better fit the existing knowledge. The need to address both sides of the process is not seen. In short, this model assumes that assimilation is the process by which new things are learned, and does not allow for the process of accommodation. Of course, for some knowledge that is the case. Certainly, most factual knowledge can be learned through assimilation alone. For example, learning that the speed of light is approximately 3.0×10^8 m/s does not require the full machinery of Piaget's scheme. A constructivist would agree that assimilation is all that is required to master this knowledge. The point is that a robust understanding of the nature of light cannot be achieved through assimilation alone.

Whatever the topic, the existing framework within the student will determine in what ways the new knowledge we are hoping to teach will be changed from the time it leaves our mouths until the time that knowledge rests within the student's mind. It is during this process that the student makes the concept his or her own. If we want the student's picture to agree with ours, we must be familiar with the cognitive tools being employed to shape the new information. Only then can we effectively address in what ways we can help the student steer the assimilation and accommodation process to lead to a scientifically sound understanding of the concept.

The Ontological Category

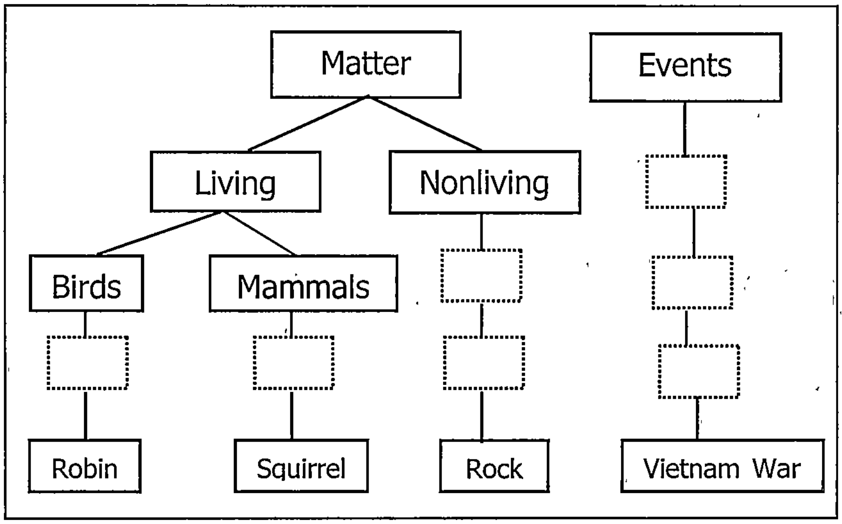
The cognitive tool known as an ontological category is best understood through example, rather than definition, but let us begin by listing some important properties as stated by Chi (1992).

1. Every category has a distinct set of constraints governing the properties of its members.
2. No physical or mental operations (such as surgery, movement, generalization, deletion, or addition of features) can transform entities in one ontological category into a different one.
3. A distinct set of predicates modifies members of one ontological category versus another.

4. Different ontological categories can be distinguished between, or entities that are in the incorrect category can be identified, by the use of the category's predicates in a "sensibility judgment task."

The view of cognitive structure afforded by the use of ontological categories is similar to a taxonomy tree. Each concept or entity within the cognitive structure belongs first to a very broad category, then to more and more refined categories as its defining characteristics are better understood. A small example of this type of structure is provided in the figure below.

Figure 2. Ontological Category Structure



Categories toward the top of the chart are increasingly general. More closely related elements within the structure find common categories without as much upward wandering. For example, the robin and the squirrel find a common category in that they are both living things. To find a category that includes the rock, I must move further up the tree to the matter category. Of course, Figure 2 is by no means meant to be a complete representation of even this small set of concepts. My intent is to provide an abbreviated example to help illuminate the nature of ontological category assignment.

Sensibility Judgment Tasks: Distinguishing Between Ontological Categories

I will now outline how sensibility judgment tasks are used to illustrate the differences between the categories (Chi, 1992). The basic strategy when forming a sensibility judgment task is to first choose a predicate that clearly belongs to one category, or a distinguishing property of that category. The predicate is then used to modify the external cognitive element (thing, event, abstraction, etc.) in question. These tasks are quite simple to understand if we choose a category and an outside cognitive element with which we are familiar. For demonstration's sake, imagine that the squirrel is a cognitive element that is to be assigned to a category and understood for the first time. Further suppose that the squirrel is to be tested as a member of the “Birds” category from Fig. 2. We can choose as one property of this category the ability to lay eggs. If we now try to impose this property on the squirrel we discover a set of nonsense statements such as, "The squirrel laid an egg", or "The squirrel has just hatched from its egg." It is important to note that what is wrong with these statements is not simply that they are false. If that were the case the statements, "The squirrel did not lay an egg," or "The squirrel has not hatched from its egg," would be proper. These statements imply impossible circumstances for the squirrel, and an uninformed reader would infer abilities that the squirrel does not have. The problem with both of these statements is that the squirrel is being given characteristics that are associated with the incorrect ontological category.

We can find common predicates between the squirrel and the robin quite easily, as they are both members of the living thing category. "The squirrel died" makes as much sense as "The robin died." If we wish to apply our predicates to members of categories that are further removed from the bird category, we must go further and further up the ontological tree to find commonalities. "The rock laid an egg" is as absurd as "The rock died." But the rock, squirrel, and robin can all be hit with a hockey stick. One cannot, however, hit the Vietnam War with a hockey stick. This is not due to a set of difficulties that are at all similar to those one might encounter when trying to hit the robin. The difficulty, of course, lies in the fact that the war is an event. Only elements within the matter category can be hit or struck. Chi (1992) makes the assertion that these varying levels of error are significant. The ease with which an incorrectly assigned concept can be reassigned is dependent upon the level at which the category mistake has been made. It is necessary to discuss how these categories are seen as part of the learning process if this point is to be fully understood: That is the topic of the following section.

Implications of Ontological Categories on Learning

It is useful to note that the sensibility judgment task is not a very effective learning mechanism. If one is unfamiliar with the outside cognitive element to be understood, the nonsense statements that result in attempting to apply ontologically incorrect predicates to the new element may not be interpreted as nonsense! The initial assignment of a new element to a category is therefore dependent upon the limited knowledge that the learner has gained, or assumes about the new element. If the initial assignment is correct, the usefulness of ontological categories in assimilating a new piece of knowledge is easily seen. The learner can immediately associate a host of properties with the new concept without the need for instruction or even contemplation of each independent attribute. Take for example my encounter with an unfamiliar bird in the forest. I immediately place the new cognitive element into the bird category based on the features of the animal that are apparent to me. It has feathers, a beak, and can fly. By assigning this creature to the bird category I gain access to a host of information about it for which I have no direct evidence. I might assume, for instance, that this animal lays eggs, is warm blooded, and has a three chambered heart. If it is well camouflaged, I might even assume it is the female of its species. The important point here is that my ability to categorize the new discovery is extremely useful for completing my understanding.

Consider now the problems that may arise if a new concept is initially assigned to an incorrect category within the learner's mind. It is easy to see how such a mistake could be made, as the initial category choices are based on the few facts about the new cognitive element that are at hand. Upon making an initial category assignment, the blanks in the learner's understanding of that concept immediately begin to be filled with the attributes of the incorrect category. The new concept is then logically assumed by the learner to possess properties that an expert would say it should not have. From a Piagetan standpoint, the student performing his or her assimilation and accommodation scheme within the incorrect category is adapting his or her cognitive structure based on a set of false pretenses. If the learner sees this process through to an equilibrium state, it will be very difficult for him or her to see the mistake in the original category assignment due to the connections that have been made for the concept in its current incorrect assignment.

I ask you to recall that, as stated above, there are varying levels of severity in the learner's category mistakes. Chi (1992) asserts that errors made in the broader categories are much more difficult to repair than those made on the lower levels of the tree. It is my opinion that when confronted with a situation in which the learner's understanding of the element in question is challenged, the learner looks only locally within the ontological tree for necessary repairs. This, of course, is not a conscious decision. To further illustrate this point, allow me to return to the rather simplistic example involving the "birds" category. Suppose that a bat is incorrectly assigned to the bird category due to the observations that it can fly and has wings. The information that the bat does not have feathers may be more likely to cause the learner to place the bat into some subcategory of featherless birds, rather than reconsider the assignment of the bat to the bird category. Awareness of the subcategory of "non-flying birds" would add support to such a decision. Clearly one doesn't remove penguins from the bird category simply because they are lacking one common trait. Rather, the penguin exists in a subcategory similar to the one in which the bat now resides. This is, of course, a rather simple example. However, the statement being made is important. It is simpler, and much more natural for a learner, to assume what has already been decided is correct, and to make amendments to that decision, rather than reexamining his or her initial assumptions.

The bat and bird matter does not provide a very convincing problem; the initial error was made quite low on the ontological tree. Most of us would be quite willing to remove the bat from the featherless bird category and place it in a winged mammal category based simply on the advice of an expert. But a mistake made further up the tree is likely to remain well outside the scope of the student's attention. One can imagine the difficulty a learner would have in recognizing an initial decision that a particular cognitive element is a thing (belongs in the matter category) as being in error. Making this type of problem even more difficult to resolve is the fact that not only is such a mistake difficult for the student to recognize, but an instructor is not likely to detect it either.

This high level error is the type that occurs for many students as they attempt to learn new physics concepts. In most of their courses, the concepts the students are asked to learn are easily identifiable as things, events, or ideas. In physics, we deal with processes and laws that constrain and conserve. To further complicate things, what is being constrained or conserved is often an abstraction itself! Suffice it to say that these topics we discuss are often sufficiently abstract to cause our introductory physics students a great deal of difficulty as they attempt, subconsciously, to incorporate them into a scheme of ontological categorization. In the next chapter, we will look at just such a situation by returning to the conversation above between a student and myself regarding electric current.

An Overview of the Landscape

The primary goal of physics education research is to improve student learning. Physics education researchers achieve this goal by studying all aspects of teaching and learning in the physics classroom. This endeavor benefits both the teacher/researcher, and the physics student. As physics teachers, we gain priceless knowledge we can use to improve our curriculum and instructional strategies. In addition, as we try to understand how our students think about physics, our own understanding of the discipline is enriched as we explore new ways to think about familiar concepts. In turn, the research enhances the students' experiences in our classrooms as we continue to provide them with richer environments in which to learn the concepts and laws of physics. In this section, I will explore some of the theories and methods that have been applied to pursue physics education research and properly place the present work within this landscape.

There exists a large body of research dedicated to understanding the nature of students' initial or preexisting knowledge of physics concepts (McDermott & Redish, 1999). It is widely agreed that this preexisting knowledge is acquired through some combination of everyday experience and intuition. Vosnaidou and Brewer (1992) provide an excellent listing of the terms used to describe this knowledge. The most widely adopted approach to physics education research is that which attempts to elicit students' preexisting alternative frameworks for physics concepts and confront those often naive theories directly through the use of innovative curricula. Such an approach will be termed "misconceptions research" throughout this section. The merit of this approach of investigating students' prior notions of subject themes is particularly apparent in the discipline of Physics, as many of the concepts and labels used have colloquial meanings that may or may not agree with their stricter definitions within our field. In addition, each student experiences real world physics demonstrations as he or she goes through life and observes the interactions of matter around them. Until the time they enter our classrooms, the task of interpreting these demonstrations belongs solely to the student. Misconceptions research holds, as an underlying premise, that students' initial knowledge state often exists in the form of a robust, if not altogether accurate theory. Indeed it is entirely reasonable to assume that the student can and will construct logical, robust models to explain the phenomenon they observe and that these models are not always in agreement with those we use as physicists. These robust models constructed by physics novices to explain observed phenomena are commonly defined within the physics education research community as misconceptions (Novak, 1987), preconceptions (Ausubel et al., 1978), or alternative frameworks (Driver & Easley, 1978). I have chosen to use the term "misconception" to refer to such models and will now outline some of the more important characteristics.

An example of a common student misconception in mechanics can be found in Halloun and Hestenes (1985). Students hold the belief that an object with a constant net force on it will move at a constant velocity. This arises from the students' experiences in a world full of friction. The student knows that when he or she begins pushing on an object it accelerates from rest, then requires a constant force to maintain its speed. The necessity of this continuous application of force is not attributed to the presence of a dissipative frictional force because the student does not directly perceive that force. The conclusion that is drawn by the students over a lifetime of such experiences is that a force is required to maintain a constant velocity. In addition, the student may also conclude that the net force applied to an object must always be in the direction of the object's motion from these experiences. Indeed, a whole set of incorrect assumptions can be drawn from the simple experiment of moving a refrigerator across a linoleum floor! This illustrates the robust nature of the physics misconception in that it arises from a lifetime of thought and experience, and encompasses several or many separate ideas. Halloun and Hestenes outline another important characteristic of misconceptions as well. In the referenced work they discuss how students' preexisting models of dynamics often resemble the historically adopted impetus theory. It is not uncommon for modern students' initial ideas about physical phenomenon to resemble theories that were held by great thinkers of the past. If the student develops a robust theory from everyday experience, one can often find a previous occurrence of such a theory being developed from the experiences of thoughtful people in Renaissance Europe, or ancient Greece.

To summarize, a misconception is a robust, coherent theory that a student has developed from experience and intuition to form a practical understanding of physical phenomenon encountered in everyday life. The "mis-" prefix illustrates that often these theories do not agree with the current scientific view. Such conjectures may even resemble historically significant scientific models that have since been rejected for the currently accepted theories. Both because the misconception is so rooted in the student's experiences, and because it is often logically constructed and internally consistent to a large extent, it is often extremely resistant to instruction: a fact that is supported by the often-observed resemblance to historical scientific theories that, while flawed, were believed to be accurate by the greatest thinkers of humanity for, in some cases, hundreds of years. There have been many successful efforts by members of the physics education community to meet the goals of our research by exploring students' prior physics knowledge and first eliciting, then resolving student misconceptions in many different areas of undergraduate physics. Much of this work can be found in the literature review provided by McDermott and Redish (1999).

Most of the work listed in the reference above focuses on student interpretations of particular physics concepts. However, it should be noted that this is not the only prior knowledge that needs to be taken into account by the physics educator. It is also necessary to consider work by researchers such as diSessa (1993) and Minstrel (1992), who discuss the nature of phenomenological primitives (p-prims) and facets. These are defined as small pieces of knowledge people use almost instinctually. Such notions as "brighter is hotter" or "bigger is stronger" are knowledge elements that are crucial for us to apply in everyday life as they are the mental processes that keep us from putting our hands on electric burners or stepping in front of buses. In some cases, it may be appropriate to interpret physics concepts or problems using these tools, but caution must be exercised. Take for instance problems involving Newton's third law. A p-prim view of student thought illuminates the fact that the deep-seated notion "bigger is stronger" contributes directly to student difficulties with this fundamental physical concept and will lead to incorrect assumptions involving problems that require the use of the third law to solve them. Very little attention is paid to Newton's third law in traditional introductory physics classrooms: After all, many students can recite "every force has an equal and opposite force" before even entering the physics classroom. The p-prim "bigger is stronger" is a much more powerful persuader than this mantra within the student, and they will apply it enthusiastically when asked whether the bug exerts the larger force, or the windshield of the truck that squashes it. Here we see how the use of p-prims and facets not only provides a powerful new lens through which to view our students and our instructional tactics, but can also point us to areas where we need to revisit our selection of the physical concepts we stress in our teaching.

The work discussed above illustrates that it isn't just a student's prior conceptions of physics that affect how they learn new concepts in our classroom. Knowledge from every corner of the student's mind may be used to either facilitate or impede our efforts to help them understand a new physical concept. This is a different approach to physics education research. A greater emphasis is placed on pieces of knowledge that students employ in broader contexts than the physics classroom. The knowledge gained by studying student thought in this more general sense is then applied to how students learn (or don't learn) the specific discipline of Physics. The use of facets and p-prims by physics students fortifies the notion that each student enters the classroom with a framework of knowledge that spans the entire breadth of their individual experiences. Any efforts by the student to learn new concepts in physics will be done within the context of that framework.

Not only does the entire breadth of an individual student's knowledge effect how easily he or she will learn a new concept in physics class, but the very nature of *how* they learn needs to be examined as well. It is here that the work of Michelene Chi (1992) on ontological categories declares its importance. Ontological categories are similar to p-prims in that the use of them by the student is an almost instinctual, and certainly subconscious, response to receiving new knowledge. In addition, the technique being applied by the student in an attempt to understand a new physics concept, say electric potential, is not a skill that is directly associated with the discipline of physics, but it profoundly effects his or her ability to understand the new physics concept. It is important to note, however, that misconceptions and p-prims are both examples of prior knowledge that the student applies incorrectly to a new physical situation. The use of ontological categories is something quite different. It is a learning technique that is being employed. In this way we are exploring a rarely seen approach to physics education research. One that investigates not how prior knowledge affects student response to instruction, but how the very process by which students attempt to assimilate new knowledge can impede our best efforts in the classroom.

CHAPTER 3

ELECTRIC CURRENT AS A SUBSTANCE

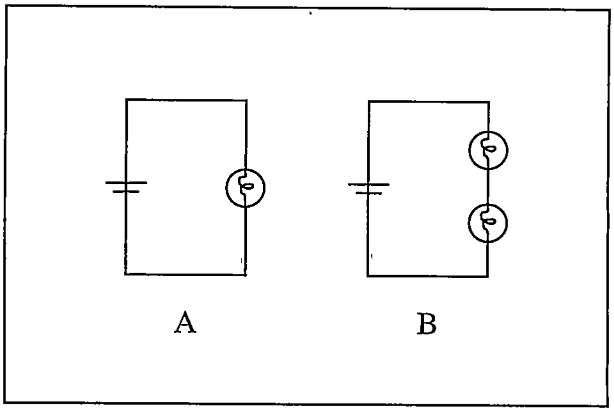
Discerning a Category Mistake

Allow me to return to the remarks made by my student that began this story. Viewing the statement, "The current is the same, but it is moving more slowly" with the assumption that the student has incorrectly assigned electric current to a material substance category sheds much light on what this student thinks is happening within the circuit. Perhaps the best way to see how an instructor can use this lens is by examining the experiment that motivated the above conversation from the perspective of the student.

Assume first that the student views electric current as a substance that the circuit of wires, light bulbs, and batteries contains. This is not a simple confusion of charge and current. Rather the substance believed to be in the circuit has little likeness to anything an expert would be able to draw from his or her own model of electric circuits. Students have many names for this substance, as will be revisited below when I discuss the preliminary student interviews conducted in an effort to gain insight into this problem. Among the most popular names are current, electricity, and power. Many students use these terms interchangeably to describe the substance in question. Until evidence is provided below, I ask that it be accepted that the student quoted above views electric current as a substance of this sort. All of the properties of this substance are not yet discerned, but by experiment and discussion with me, the student hopes to flush them out.

The Physics by Inquiry (McDermott et al, 1996) curriculum asks the student to compare the brightness of the bulbs in the circuits illustrated in Figure 3.

Figure 3. Circuits



The student makes the observation that the bulbs wired into the circuit labeled B in Figure 3 are dimmer than the bulb in the circuit labeled A. It is clear from the statements in Chapter 1 that the student perceives a change in the current as being responsible for the change in bulb brightness. However, the student does not agree with the correct conclusion that it is a change in the *amount* of electric current that is responsible. It is logical to assume that for this student the statement, "there is less current in circuit B" would imply a smaller quantity of the electric current substance within the wires and bulbs. There are several possible explanations for why this doesn't strike the student as being reasonable. If we allow that electric current is this ill-defined substance, it seems most reasonable that it is either conserved within the circuit due to a constant source (the battery), or even that the addition of more elements makes circuit B capable of housing more current! At any rate, the student has clearly decided that the amount of this substance in circuit A is the same amount to be found in circuit B: "the current is the same amount." The student has chosen the speed of the current as the discrepant variable between the two cases and attributed the observation of the dimmer bulbs to a slower movement of the substance: "the current is the same, but it is moving more slowly."

To further illustrate the importance of my attentiveness to this problem, I'll point out a tragic mistake that I, sadly, know I have made in the past. If I correct the student who states that the current present in the two circuits illustrated in Fig. 3 is the same, I force the student to adjust his or her interpretation of the behavior of electric current. I say, "Well, the fact that the bulbs are dimmer in circuit B implies that there is less current in that circuit." As stated above, it is my belief that the student looks only locally within the ontological structure to repair discrepancies that arise in his or her interpretations. As an expert, my disagreement with the student will force such a change, but not at the appropriate level. Rather than reexamine the initial subconscious choice of electric current as a material substance, the student looks to justify the existence of less of the substance within circuit B. A logical conclusion would be that the presence of the second bulb has caused this reduction in the quantity of the substance. The student may conclude that the bulbs are absorbing or consuming the substance in some way. This will allow the student to agree with my assessment that there is less current in circuit B, but unfortunately a flawed model has just been made worse by my intervention. I admit that I have, in the past, further complicated this situation by insisting later in instruction that elements within a circuit do not consume electric current. If my belief that the initial ontological mistake is out of the student's scope when searching for error in the model, the student may now conclude that it will be easier to memorize facts about this current stuff in various situations than to try to repair his or her obviously flawed understanding any further.

Substance-like Electric Current

We have in electric current a concept within physics in which an early ontological mistake can easily occur and remain unnoticed by the student throughout instruction. I have no doubt that there are other abstract concepts within our discipline that also provide opportunity for the study of this phenomenon. Several, including electric current, are proposed by Reiner, Slotta, Chi, and Resnick (2000). My purpose here, however, is to examine carefully this one subject. My belief is that what can be learned from a careful study of electric current in this manner should be largely applicable to the study of other physical concepts that pose this same problem for our students.

Why the initial assignment of electric current to the substance category occurs is fodder for debate. Perhaps the category is a default choice whenever a new concept is introduced. After all, most of what a person interacts with in life is material substance and not abstraction of some kind. When speaking of electric current, the language used by experts can only serve to reinforce the belief that it is a substance. We often say things like, "the current splits up at the junction, " or "part of the current goes this way," or "the current goes from the battery to the bulb and back again." For experts, this kind of language is natural and useful; we are firmly rooted in our belief that electric current is the movement of charge and that it is measured in coulombs per second. But for the student, who wishes to think of current as some sort of electrical juice that is kept in the battery and released to flood the circuit, this language is interpreted quite literally. This problem of language is difficult if not impossible to overcome. On the most fundamental level of dialogue, we use electric current as a noun, and most nouns are matter. I do not advocate a complete revamping of classroom language when addressing this topic, although I do think one should take note of what his or her statements may mean to students in light of their substance-like beliefs. Rather, I hope that by giving students a rooted understanding of what electric current is, the traditional language can be used without confusion.

An interesting question is raised when one considers why it should be so difficult for a learner to recognize such a fundamental mistake as this very broad ontological error. In the case of electric current, it is my feeling that the degree to which this initial assumption is supported by other knowledge elements within his or her cognitive structure contributes to the difficulty in recognizing the early error. A substance-like model does in fact lead the student to some correct assumptions about the behavior of electric current. Most notably, the conservation of electric current in and out of a node within the circuit is good support for such a model, and will be reinforced by instruction. Confounding the problem is the ease with which students can make small repairs to their understanding that permit what an expert would consider a misconception-breaking discrepant observation. A student can simply attach a qualifier to the electric current cognitive element deep within the material substance category. To put it simply, when presented with the information that the two bulbs in circuit B from Figure 3 above get the same current, and that neither bulb is consuming current, the student can say, "Ok, so this electric current stuff is not consumed or used up." The student creates a sub-category within material substances. This is a much more common form of learning for us all, similar to the kind of remedy, or conceptual change, that would be appropriate if the mistake were made on the level of the bat as a bird discussion in the previous chapter.

Because a flawed model can obviously still lead to correct answers, a student with a substance-based model of electric current can answer correctly many of the common questions we pose when studying circuits. Assuming, of course, that the student in question has a complete set of qualifiers refining the behavior of this substance. Certainly a very mathematically rooted and equation driven problem can be solved by a student with little conceptual understanding. It is not this type of question I refer to. We may in fact expect to see students with flawed, but partially repaired electric current models answer some very rich conceptual problems correctly as well. This assertion of mine suggests two questions that should be addressed from the onset. The first is, why should I care if my students treat current in this way? If they can use Ohm's Law and perform this bulb ranking task and so on, isn't that good enough? I maintain that thinking of electric current as a material substance represents a lack of understanding of the concept at the most basic level. How can students truly understand the behaviors that they are describing with the use of Kirchoff's or Ohm's equations if they do not even understand what current is? I feel that students who support these ideas have missed the point of what I was trying to give them through my instruction. I would hope that a coherent, useful model of the behavior of electric circuits was developed, including a conceptual understanding of what electric potential, charge, electric current, and resistance are and how they interact to govern a circuit's behavior. Not solely for the purpose of enabling the students' predictive powers in this subject, but more importantly to provide them with an understanding that the construction of such models is a big part of the fundamental goal of physics in general. Students who still think of current as stuff do not have such a model. The substance-like electric current model shored up with qualifiers can hardly exist as part of a complete understanding of electric circuits. It is likely that students with such a model would have similarly bandaged models of electric potential, etc. that exist quite separately from their view of current. Indeed such students may not have models at all, but rather piecemeal sets of memorized facts about current that I spouted, or they inferred, throughout the section.

The second question raised is as follows: If the students can answer complex questions about current with a flawed or nonexistent model, how can one test them to see if they hold this belief that current is a substance or has substance-like properties? The task of developing a questionnaire capable of identifying this ontological mistake is the topic for the following chapters. For now, I will assert that many, or even most, of the introductory students we see enter our classrooms have a tendency to treat electric current as stuff, and they leave our classrooms with that same tendency. Below, I hope to persuade you of this fact with my data!

CHAPTER 4

THE IN-CLASS WRITING TASK: A PRELIMINARY STEP

As a preliminary stepping-stone to the development of a questionnaire aimed at testing students' substance-based views of electric current, I asked 15 students from a class using Physics by Inquiry (McDermott et al., 1996), taught at Montana State University as Physics 201, to respond to an in-class writing task. The task was given to students before any instruction on electric current had occurred. They were asked to write for five minutes on the following question:

"A knob on the side of a desktop lamp turns it on and off. Describe in your own words what must happen to make the lamp light."

My hope in constructing this task was to determine whether or not this simple, everyday event would produce student responses indicating the degree of belief in electric current as a substance. A typical student response to this task that shows a substance-like model follows.

"*When you turn the knob on the lamp you are opening a path for which the electricity passes through. When you turn it off it is closing the path and stopping electric current.*"

Perhaps you already see the implication of a substance-based view of current within these sentences. However, a more rigorous scientific method of analyzing the statement than mere inspection can be applied. We will see in the next section how to identify substance-based reasoning in this student's statements.

Discerning Substance-Based Reasoning Through the Use of Predicates

Using an analysis scheme developed by Slotta, Chi, and Joram (1995) we can analyze this statement for indications of a substance-based conception of electric current. Slotta et al. define a set of "verbal predicates" used by students that can reveal students' use of an underlying substance-based model. A predicate is the part of a sentence that tells something about the subject. In the context of this work, the predicates of interest are those that reveal the speaker's ontological assignment of the subject. I will provide here only the predicates that directly apply to this work and the development of the questionnaire. I feel, based solely on experience with students, that this subset of the taxonomy developed by Slotta et al., which is presented in its entirety in the reference provided, represents the most commonly used predicates directly attributable to substance-based modeling of electric current. The difficulty presented linguistically by the simple grammatical fact that electric current is a noun makes it more challenging to determine whether or not a student's use of some of the predicates in this taxonomy truly represents an underlying substance-based model, or are simply a grammatical convenience.

An application of Slotta's predicates to the topic of electric current suggests that a subject with a substance-based model is likely to treat current as though it behaves in one or more of the following fashions (Slotta et al., 1995).

1. Electric current can be *blocked, contained, or stopped.*
2. Electric current *moves* in a way that is inappropriate. This is closely related to the idea that it is *supplied* and "comes from" one place and "goes to" another.

3. Electric current can be *absorbed* or *consumed.*

I have italicized the material substance predicates in the list above. Slotta et al. attempt to uncover a subject's underlying substance-based beliefs by documenting the use of predicates that inappropriately assign a substance-like ontology to the concept under investigation. A substance-based model of electric current, for example, may be indicated by the use of some or all of these predicates. By recording the frequency of material substance predicate use, Slotta et al. seek to discern the degree to which the subject is making an error in ontology. In my list, I've grouped some of these more closely related predicates together to form three categories of substance-based reasoning. My grouping is an effort to categorize three types of behavior students may attribute to electric current within a circuit. When developing questions for students to examine, it is very difficult to isolate just one of the ideas represented by the use of a single predicate. Indeed, it is difficult enough to attempt an isolation of one of these three broader measures. For this reason, as well as the linguistic difficulties mentioned above, my method for uncovering substance-based reasoning differs from that of Slotta et al. They are listening for the actual verbal use of predicates in his taxonomy: I have grouped these predicates into categories that represent behaviors that will result in incorrect predictions of current behavior. This grouping is a foreshadowing of the questionnaire items developed below which are designed to determine the degree to which students will reach incorrect conclusions about electric current that are consistent with these three more general categories of behavior.

Special attention must be paid to the category involving the *move* predicate as it represents a difficult interpretive task linguistically. Many experts will speak of current as "moving" through a circuit. When questioned, however, they will reveal that what they are really referring to is a movement of charge, not electric current. Speaking of electric current as moving for an expert is a convenience that allows the omission of cumbersome dialogue concerning a measurable net flow of charges. On the other hand, students will refer to *electric current* moving. This may seem subtle, or even unimportant, but it leads the student to severely incorrect modeling of the behavior of electric current including the belief that the current can exist in one part of a complete circuit, but not another, and that it can "come from" the battery and fill the circuit like a fluid. Of course, a student will interpret an instructor's use of the word "move" as being in agreement with his or her own mental model, further bolstering an incorrect view of electric current. Again, we see that the lack of precise language for the concept of electric current introduces some difficult instructional barriers. If we hope to identify this problem of treating current as "stuff" within our students, we must be very sensitive in our interpretation of the language that they use. Furthermore, if we hope to correct the problem we must be even more sensitive to how they are interpreting the language that we use.

We can be optimistic that the verbal predicates and the categories of behavior as I have grouped them can at least provide us with cues to look for in students' verbal or written statements about electric current. Let us try to apply such an analysis to the student response to the writing task presented above. One interpretation of the student's comments might be that the phrase "opening a path for which electricity passes through" is an indication of category-two reasoning as it was defined above. The student sees the current as being released into the circuit in some way when the switch is turned on. The current, or "electricity" as she names it, is then interrupted when the switch is turned off. The electricity then comes to a stop. This second part of her statement clearly indicates category-one reasoning. It is reasonable to conclude that the student is treating electric current as a substance.

Results of the In-class Writing Task

The results of this little experiment were quite good. I use the term "good" with my researcher's hat firmly in place: Often, in examining student difficulties I find that I can become overwhelmed and depressed if I'm wearing my instructor's hat! Nine of the fifteen students directly indicated beliefs consistent with one or more of the categories of material substance behavior in their responses. Four of the remaining six responses did not refer to electric current in their explanation, the other two said nothing that allowed any discernable hint of what they thought was lighting the bulb, making it impossible to either confirm or deny any suspicions of their use of a substance-based model.

The success of this simple task in eliciting incorrect ontological category assignments for electric current within the students prompted me to develop an interview protocol. The purpose of the interview was to extend the students' attention to this question, as well as to focus on very simple everyday experiences with electric current both in and out of the classroom environment.

CHAPTER 5

INITIAL STUDENT INTERVIEWS

The same population of Physics 201 students that responded to the in-class writing task was asked to participate in a short interview to discuss their responses. The four participants were given no award or compensation for their help. Taking willing volunteers from a population may introduce some self-selective effects. It is reasonable to assume that the interview participants are more motivated students who are more anxious to help their instructors than the average student within the classroom population. I think it will be clear from the dialogue they provide that any effect of this selection only strengthens the arguments made below. The interviews were concurrent with instruction in electric circuits in the classroom but were held outside of class. The interviews were tape-recorded with the participants' approval. The interview protocol and transcripts are included in Appendix A.

The purposes of the interviews were to further inform me of the nature of student substance-based modeling and to assist in the development of a written instrument that could be employed to assess large numbers of students. The interviews were informal. The protocol provided a guideline, but often the interviews wandered freely into other areas of discussion as the students questioned and explored, and I searched for insight and perhaps some good questionnaire items. Some of the students' comments, while interesting, did not lead to future questionnaire items and so are not discussed here. For this reason, complete transcripts of the interviews are provided in Appendix A; only informative excerpts are provided here. The names of all interview participants have been changed as they were promised anonymity.

Excerpts from the Interview with "Jesse"

Jesse's interview is worth examining very carefully, as he provides aspects of a model that we will see reflected by the other interviewed students when we turn our attention toward them below.

As the interview begins, Jesse and I are discussing the lamp question he was given as a writing assignment in class. Jesse's written response to the in-class writing follows.

"The knob completes the circuit. A piece of metal connected to the knob conducts the electricity making the light turn on when pushed."

Jesse shows some prior knowledge of electric circuits in his response, including some rudimentary notions of the role of conductors, switches, and the need for a complete circuit. There is nothing incorrect in what he has said, but whether or not he views electric current as a substance of some kind is inconclusive. He made mention of "electricity", which I think is safe to assume is analogous to what we would call electric current, but he didn't go into any details of its behavior. My initial statement is an effort to prompt him to further discuss the nature of electric current and "electricity".

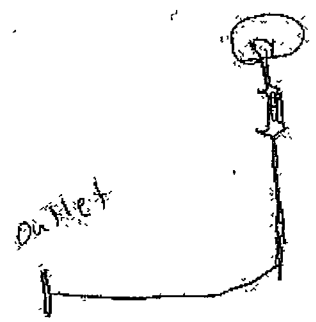
T: So we plug our lamp in. Talk to me about what happens with the electricity or electric current before I turn the lamp on.

J: Ah, it comes up to where the switch is and then it has to stop because there is not a connection.

T: OK can you draw a picture for me...a representation of what's happening.

Figure 4 shows Jesse's picture; his dialogue as he draws it is included in the following quote.

Figure 4. Jesse's Drawing



J: This is our outlet here, then we got our cord coming up to our lamp post, then we got the light here. There's a switch somewhere in here (draws in the upper horizontal line on the lamp post) *that when you slide it forward...the current is stopped right here before it gets to the switch* (draws in the lower, horizontal line on the lamp post), *so there's a space in here and when you turn the switch it pushes down and completes the circuit so it can flow up into your lamp.*

In this dialogue, Jesse has implied two of the material substance predicate categories discussed in the previous chapter. His picture and description both clearly indicate a belief that electric current *moves* in an inappropriate way and that it is *supplied* (category-two behavior). He also indicates that he believes the current is stopped at the switch and is at rest in the wire before the switch is closed (category-one behavior). He again shows good understanding of the need for a complete circuit and even shows knowledge of exactly what the switch is doing. However, Jesse is certainly treating electric current itself as a sort of fluid substance within the wires that flows out of the wall and is not allowed to pass through the switch, and so must come to a stop until the switch is closed. I then asked him to think about what happens when we turn the switch to the on position.

T: So after we turn it on we get current that comes up into the light bulb. What happens to it then?

J: Then it comes up in here (gestures to the bulb in his picture) *through your filament…makes the bulb go…and then it's spent.*

T: What do you mean spent?

J: I don't know just spent, all used up I guess

Here we see Jesse employing the third category of substance-based behavior: His reasoning is consistent with the notion that the current is *consumed.* It can safely be said, even at this early stage in the interview, that Jesse is strongly anchored in his assumption that electric current is a material substance, having seen him draw conclusions consistent with all three categories of substance-based behavior. The following dialogue involves a question that is eventually included in the questionnaire. The student is asked about two identical lamps, one with a much longer cord than the other.

T: Say I've got two of these lamps, identical in every way. You and I each take a lamp, and I have 1000 feet of extension cord. I plug my lamp into the extension *cord, the extension cord into the wall. You plug your lamp into the wall. We go over to the knobs, take hold of them, count to three and turn them on at the same time. Do the lamps start glowing at the same time?*

J: Probably not exactly but as close as we can tell. No, I take that back because the current is still going to go up that extension cord and be waiting at the switch to be connected.

Here Jesse shows remarkable consistency in his reasoning. The *moving* and *stopping* behavior that he imposes on the electric current in his initial statement governs his decision making on this question as well. However, perhaps because of his belief in the *movement* property, he stumbles for a moment and allows for the possibility that it might take a little longer for the current to travel down the extension cord to the filament. This type of reasoning prompts the next question.

T: So lets change the problem a bit. How about before we plug them in...we've got the lamps unplugged and I've just hooked mine up to the extension cord, that's all we've done. We turn our switches on, and then we go over to the outlet, count to three, and plug them both in...then what happens.

J: Mine's going to turn on a little bit faster, but not that you could tell.

T: So if I had a thousand miles of extension cord would we be able to tell?

J: Probably.

T: How about after we've had them lit for a while we go over to our knobs and we turn them off at the same time.

J: They turn off at the same time.

T: Instead of doing that we go over to the plug and we both unplug them at the same time.

J: I guess I'd have to say there would be a little bit of difference again.

It is important to note here that there is some truth to some of Jesse's conclusions. After all, information must travel at a finite speed, and it would in fact take fractionally longer for my lamp to light. It is clear, however, from Jesse's earlier statements that this is not the line of reasoning that he is following. He actually sees a substance, which he identifies with the current, rushing out of the wall to fill the wire and eventually light the filament. This fluid-like electric stuff takes a little bit longer to travel down the extension cord than the short cord. It is my belief that Jesse is resolving the discrepancy between his model and what he actually observes by assigning a very high speed to the fluid. Of course, an expert would say that the current itself is not rushing out of the wall. Rather there are electrons throughout the wire and filament, and when the switch is closed they experience a force due to the presence of an electric field and begin to flow. This movement is what we call electric current. For all intents and purposes the bulb lights immediately. The current does not take any time to get to the filament because it "comes into existence", if you will, at the filament and everywhere else in the circuit at the same time. This is a simplified model. In reality the two lamps may experience small but finite differences in their lighting times due to the different cord lengths: if I choose as my "switch" the method of plugging them into the wall. As the lamp cord is plugged in, an alternating electric field (and hence the movement of charge) would propagate outward from this switch at 3.0×10^8 m/s. The lamp with the longer cord would light second as it is further from the "switch". This discrepancy in lighting time is a much more subtle point than one I would expect a student in an introductory course to incorporate into a circuit model. The notion that the movement of the charge defines the current, and that those charges exist throughout the circuit before I close the switch is, however, a fundamental piece of understanding for the student to gain in a study of electric circuits. In my opinion, such an understanding represents a sound picture of what electric current is: a movement of charge. That the charges begin moving everywhere in the circuit at once in response to the potential difference that has been established provides the student with a strong internal model of how current behaves and makes transparent such statements as, "the current is the same through all elements in a series circuit." This simplified model, had Jesse been in possession of it, would have prompted him to say that the two bulbs in the lamps would light and go off simultaneously as they were plugged in to or pulled out of the wall outlet. For introductory students, and indeed for everyday use by most experts, I think this should be viewed as a correct response.

It can clearly be seen from Jesse's responses that he is prone to applying a substance-based model of electric current in his reasoning. It is interesting to note, however, that he is not uniformly consistent in his agreement with the various predicate behaviors throughout the interview. In the first excerpt, we see Jesse indicating that the current stops when it gets to the open switch. However, when asked directly whether or not electric current could be at rest, he responds as follows.

T: I'm a person who can run, but right now I'm not running. I'm at rest. Can electric current be at rest?

J: No, I don't think so.

T: Why not?

J: Well I know you can't cut a wire in half and have the current just stay in the piece of wire. It has to have a circuit.

Jesse's inconsistent use of his model is perhaps an indication that use of the word "model" is inappropriate. Perhaps Jesse's existing knowledge in this regime is not that well defined. After the interview, I pointed out that Jesse's final statement conflicted with his initial reaction to what would happen if I plugged the lamp into the wall while it was turned off. He realized that his description of this event, and the picture he drew were in error. We talked for some time about the nature of electric current and why it couldn't behave that way. The conceptual change needed for Jesse to stop thinking of the electric current as a substance is a difficult one, and I fear he was only loosely pasted together when he left my office!

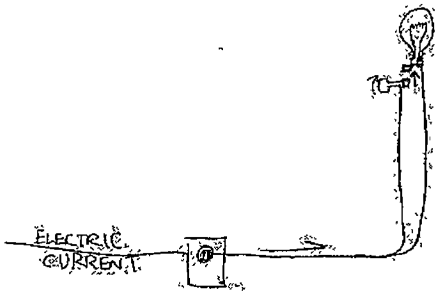
Excerpts from the Interview with "Alan"

We can see some of the same substance-based modeling in my conversation with Alan. His response to the in-class writing shows a similar amount of previous knowledge to Jesse's.

"When the knob is turned a switch connects two pieces of metal which conducts the electric current thru the wires to the bulb."

Figure 5 shows Alan's picture of what he believes is happening when the lamp, which is turned off, is plugged into the wall. His description of his drawing follows.

Figure 5. Alan's Drawing



A: Got the electric current coming here to the outlet…then from the plug to the cord to the lamp….course flows that way and up the lamp….got a little ah…suppose we put the knob there which is connected to some sort of metal piece here which when you turn it comes into contact with another metal piece.

T: So before we turn the knob, what have we got?

A: Ah you've just got electric current going as far as the knob.

T: Now go ahead and turn the knob and what happens next.

A: Turn the knob…and then I suppose, say this piece moves into contact with another piece. That completes the circuit…got your bulb here with filament inside…these pieces connect and it goes up through the filament and back down. ..completes the circuit I guess.

Alan's comments demonstrate that *blocked* and *stopped* properties (category-one behaviors) are at work in his response, as is the *move* category (category-two). He does not, however, indicate that the current is consumed by the bulb as Jesse did. Alan's beliefs are reiterated in his responses to the following items.

T: I have my thousand foot cord, and you have your five foot cord. Before, we plugged them in and went over and turned the knobs on. Now we'll do something a little different. They're unplugged, we turn the knobs on, we go over and plug them into the wall.

A: That may take a little longer, I don't know. It may take a little longer for electricity to travel a longer distance.

T: I'm a person, and I can run. But right now I'm not running. I'm at rest. Can electric current be at rest?

A: Yeah, I suppose it could before the switch is turned. I mean it's just sitting there waiting to flow.

Alan is consistent in his use of these substance-like behaviors. The remarkable similarity between Alan and Jesse's reasoning is echoed in the following excerpt from interviews with Diane and Dawn.

Excerpts from Interview with "Diane"

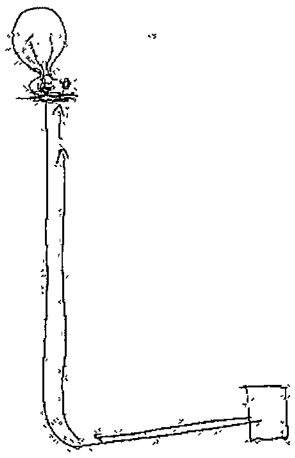
The portions of Diane's interview that reflect similar reasoning to Jesse and Alan are provided below. In particular, note that all three students draw essentially identical pictures, all showing the electric current filling the wire to the point where the open switch causes it to "stop". Diane uses the term "energy" not in the way that an expert would, but rather as a name for her particular version of substance-like electric current.

D: The energy is running to the end, but there's no connection so it can't complete the whole circuit.

T: Can you draw a picture, just your best guess, to represent the current and the lamp before I turn the knob on?

Figure 6 shows Diane's drawing, which is almost identical to the other students'. Her description as she draws it is given in the following quote.

Figure 6. Diane's Drawing



D: The energy is coming up through here and then it goes up through here and then that's where it stops.

T: Can you draw where it stops?

D: It's probably right here. (Draws the dark horizontal line at the switch)

T: So, say I have two identical lamps and the only difference is that one of them is plugged into a thousand feet of extension cord and then into the wall and the other one is plugged directly into the wall. If you and I stand by the two lamps and count to three so that we turn the lamps on at the same time, do they light at the same time?

D: Yeah. Because the energy is already there up to the point where it stops.

T: Can you bring electric current to rest?

D: Like, you have one but it's just not doing anything?

T: Yes, like I'm a person at rest I'm not running or doing anything, I'm at rest.

D: It can travel to a certain point and then not go anywhere.

T: Is at rest at that point then?

D: No I don't think it can be at rest.

Diane shows a similar model to Alan, but is less sure of her reasoning. She was reluctant to say much, and had to frequently be prompted to respond. It was clear that as the interview progressed she knew her model was incorrect and didn't want to show it. I think perhaps one of the best indications of this is her reaction to my question about whether or not electric current could be brought to rest. She clearly sees the current as having the ability to both *move* (category-two) and *stop* (category-one), but she doesn't like the conclusions that her picture provides her.

Excerpts from the Interview with "Dawn"

Dawn was extremely talkative and explorative in her interview. She had a difficult time answering questions directly but did quite a bit of pondering. Her model of electric current was clearly in a state of confusion as she was trying to include some of the things she learned in class with a gut level assumption that current is a fluid-like substance of some kind. She seemed to think that this fluid can never come to a stop, although she responded with "I don't know" when asked whether or not electric current can be at rest. I invite the reader to analyze Dawn's complete interview in Appendix A to confirm my analysis of her model.

Some of the more interesting comments Dawn made came from a discussion regarding the behavior of current in electric sockets. In particular, we discussed whether or not a person needed to worry about being shocked when changing a broken light bulb.

T: If I had a broken bulb stuck in the socket of a ceiling lamp. Should I be worried about being shocked by that?

D: Yes.

T: What if I turn the lamp off?

D: Yes, because until you unplug it the current is still flowing through the lamp. Even if...well maybe...ooo I don't know...

T: What if I went to the fuse box and pulled out the fuse for that room. Would I worry about being shocked?

D: So that circuit is broken, but the rest of the house is still working, the lamp is still plugged in...but I don't think there'd be any electricity in the room so you'd be safe then. I would think it starts at the fuse box and works it way to the socket and then works it way up to here. (indicating the switch)

T: So before I turn that knob there's no electricity or current in the socket?

D: No there is current in the socket because if you were to stick a knife into the socket you would get shocked.

Dawn is clearly of the opinion that electric current is contained in various objects and is unsure of whether or not it is still there when you turn the appliance off. She is sure that it is always in the socket, because if she touches it with a knife, she'll get shocked. In her interview she clearly shows a great deal of confusion, as well as a belief in both the *move* and *contained* properties of substance-like electric current.

Implications of the Initial Set of Interviews

All four of the subjects interviewed showed strong signs of a substance-based model for electric current. The remarkable similarities in their treatments of electric current suggest that this is not coincidence, but rather a common belief among students. In particular, questions involving the ordinary household lamp prompted all of them to suggest that the electric current fills the wire between the open switch and the outlet when the lamp is initially plugged in, and then stops. This is analogous to what happens when you turn on a garden hose at the spigot but have a shut nozzle at one end. Such a model illustrates both the *stopped* (category-one) and *move* (category-two) properties of substance-based reasoning. There were also indications of the *consumed* (category-three) type of reasoning, but it was less common. This is interesting in that much of the misconceptions literature in electric current focuses on this latter error, one that was secondary in the interviews to the other two categories outlined above (McDermott & Redish, 1992). Of course, these mistakes are easily overlooked unless one is asking the right questions!

One difficulty remains before this type of questioning can be applied to large groups of students. What if an expert's responses to these questions could not be discerned from those above? Then I would have to reject the hypothesis that the analysis

I have presented above indicates a mistake in the students' categorical representation of electric current. The next chapter explores this matter through expert interviews.

CHAPTER 6

ITEM VALIDATION: EXPERT RESPONSES TO THE INTERVIEW

Three "experts" were chosen to respond to the interview questions in an effort to determine whether or not their responses could be construed to be in agreement with a substance-based model of electric current. If such an assumption could be drawn from the responses of physics experts, then clearly the interview questions are either loaded in some way, or the linguistic difficulties mentioned previously are too difficult to overcome. I chose the participants to represent three different levels of expertise in electric current. Grant is an award-winning instructor of introductory physics. Cathy is a graduate student and teaching assistant working on her master's degree in Physics. Amy is an accomplished senior-level undergraduate student in physics. Complete transcripts of the expert interviews are provided in Appendix A.

Excerpts from the Interview with "Grant"

Here is Grant's response to the initial interview scenario. This is essentially the same question as that which was given as the in-class writing task to the students.

T: The first question involves a lamp, just a regular household lamp, with the switch turned off. I plug the lamp into the wall. Talk to me what happens with the electric current in the lamp's wire or the wall.

G: There would be no current in the wire and the wall because there is no closed circuit. When the knob is turned on the circuit is closed. The voltage or electric push *changes polarization or direction sixty times a second back and forth. The charges that make up the flow of current in the wire don't move all that fast, they don't really get anywhere. So essentially they just start wiggling in there, warming up some parts of the wire more than others, in particular the filament.*

Grant clearly shows a very different picture than that provided by the students. The fact that he includes reasoning associated with AC current is significant, but really not the main point. He recognizes that current is defined as the movement of charge, and that no such movement is occurring before the switch is closed. This leads to his statement that there is no current present where the students envisioned current filling the previously empty wire when the lamp is plugged in.

Here are Grant's responses to the line of questioning involving the lamps with different cord lengths.

T: If I take an identical lamp, and plug it into 1000 feet of extension cord, and then plug the extension cord into the wall, and we turn the two lamps on simultaneously, do they light at the same time?

G: Yes. The charge that actually lights the lamp doesn't have to come from the wall to the filament. The wires are already electrically neutral. They already have as much charge as they're going to and all that happens is that when that switch is switched, the wiggling starts. Ultimately, the wiggling is dominated by an electric field, which is set up at the speed of light. Given the fact that your room is not that far across, it would be about the same time.

T: So if we change the experiment a little bit and this time have the two lamps with the switches on, and plug them in simultaneously, do the lamps light at the same time?

G: Yes, just a different form of switch

Again we see a very different response than that offered by the students. In fact, Grant explicitly points out that electric current does not come from the wall to the filament. He applies instead a model similar to the correct model discussed previously. Even though he is aware of, and mentions the discrepancy in lighting times due to the electric field propagation being limited by the speed of light, his initial response is that the lamps would light simultaneously and he only includes this subtlety after his initial explanation. Although he repeatedly speaks of things moving in the wires, it is impossible for us to assign the use of the *move* category of reasoning (category-two behaviors) as he clearly does not mean that electric current itself is moving within the wires. This point is made even clearer by his response to the final question.

T: I'm a person and I can run, but I'm not running, I'm at rest. Can electric current be at rest?

G: No, charge can be at rest, but current is charge in motion.

Grant's responses can hardly be construed in any way to support a claim that he uses a substance-like model of electric current in his reasoning.

Excerpts from the Interview with "Cathy"

As was stated earlier, Cathy is a graduate student and teaching assistant. Here are her statements in regard to the in-class writing question.

T: (Introduces lamp and activity) I've got the lamp plugged into the wall, but the switch is in the off position. Talk to me about the current in the wires and in the wall.

C: There's no current in the wire.

T: Can you give me an explanation for why that's so?

C: The cartoon I have in my head is like the wires make up a loop and there's a break in this loop. The electrons are little dots that are lined up right next to each other. Because of the break in the wire, they're just stationary.

Cathy provides an interpretation similar to Grant's. Although she never explicitly states how she defines electric current, it can certainly be inferred from her statement. Here is her response to the line of questioning involving the lamps with differing cord lengths.

T: Say I had two identical lamps, the only difference is that one lamp is plugged into 1000 feet of extension cord. The other is not. I plug them into the wall, and you and I grab hold of the knobs and count to three and turn them on at the same time. Do the lamps light at the same time?

C: Yes

T: Why?