12-1999

Students' Mental Models of Electricity in Simple DC Circuits

Andrew C. Isola III
Western Michigan University

Follow this and additional works at: https://scholarworks.wmich.edu/dissertations

Part of the Educational Assessment, Evaluation, and Research Commons, and the Science and Mathematics Education Commons

Recommended Citation
https://scholarworks.wmich.edu/dissertations/3249

This Dissertation-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
STUDENTS’ MENTAL MODELS OF ELECTRICITY IN SIMPLE DC CIRCUITS

by

Andrew C. Isola III

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Science Studies

Western Michigan University
Kalamazoo, Michigan
December 1999
This study presents the results of research into middle school students’ knowledge about the nature and mechanisms of action of electricity in simple DC circuits. Sixth, seventh, and eighth graders (n=99) were asked a series of questions about the roles of bulbs, batteries, wires, and electricity in circuits. Almost half the number of students (n=42) were found to have used detailed, well-defined, and logically consistent mental models based on their responses. A total of 15 different detailed mental models were documented in these students that belonged to one of four different general model types: (1) round trip flow using both ends of the battery, (2) round trip flow using one end of the battery, (3) one way flow using both ends of the battery, and (4) one way flow using one end of the battery. These models were composed of eight different components that each represented the students’ conceptions of different parts or aspects of the circuit. A majority of the students (n=75) were found to have used one of the general model types, 22 used more than one general model types, and 2 were categorized as undetermined as to whether they used any or no general model type at all. A theoretical framework is outlined which explains the formation of initial, synthetic, and scientific models and how this study
informs that framework. The relationship between mental models and conceptions and how it relates to this study is also discussed.
Copyright by
Andrew C. Isola III
1999
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Bob Hafner, for his extreme patience with me as I slowly plodded through this entire project. He was willing to stick with me even after many months (years) had passed with very little sign of progress on my part. He gave me every possible opportunity to get back on track and keep moving even when I didn’t always take advantage of those opportunities.

I would like to thank the other members of my dissertation committee, Dr. Poel and Dr. Trenary, for their guidance in the search for clarity and for proofreading the whole document with a fine tooth comb.

I would also like to thank the Office of the Dean of the Graduate College for the three extensions they granted to me to be able to complete my degree program.

Lastly, I would like to thank my lovely wife who continually gave me support and encouragement throughout this whole process. She patiently put up with my being gone for long hours and many days while taking care of our four children as I spent more time staring at a computer screen than her. Thank you Vicki. I love you.

Andrew C. Isola III
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ ii
LIST OF TABLES ................................................................................................................. vi

CHAPTER

I. INTRODUCTION .............................................................................................................. 1
   Historical Context of This Study ........................................................... 1
   Research Questions .................................................................................... 3
   Significance .................................................................................................. 5

II. REVIEW OF RELEVANT LITERATURE .................................................................... 9
   Introduction ............................................................................................... 9
   Mental Models .......................................................................................... 9
   Intuitive Knowledge ............................................................................... 16
      Knowledge in Pieces ........................................................................ 16
      Knowledge as Mental Models ....................................................... 17
   Student Conceptions of Electricity .................................................... 20
   Summary of Previous Research ......................................................... 32
   Pilot Research ......................................................................................... 36
   Summary .................................................................................................. 41

III. METHOD .................................................................................................................. 44
   Introduction .............................................................................................. 44
Table of Contents—Continued

CHAPTER

<table>
<thead>
<tr>
<th>Subject</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects</td>
<td>44</td>
</tr>
<tr>
<td>Materials</td>
<td>45</td>
</tr>
<tr>
<td>Procedure</td>
<td>46</td>
</tr>
<tr>
<td>Scoring</td>
<td>47</td>
</tr>
<tr>
<td>Grouping of Students</td>
<td>49</td>
</tr>
<tr>
<td>Construction of Mental Models</td>
<td>52</td>
</tr>
</tbody>
</table>

IV. RESULTS........................................................................................................ 54

| Introduction                              | 54   |
| Distribution of Groups                    | 54   |
| Group 1 Data Analysis                     | 56   |
| Descriptions and Distribution of Mental Models | 61   |
| Group 2 Data Analysis                     | 64   |
| Descriptions and Distribution of Mental Models | 69   |
| Group 3 Data Analysis                     | 71   |
| Descriptions and Distribution of Mental Models | 77   |
| Summary of Data Analysis for Groups 1, 2 & 3 | 79   |
| Summary and Distribution of Mental Models  | 81   |
| Group 4 Data Analysis                     | 92   |
| Analysis and Distribution of Possible Models | 95   |

V. DISCUSSION.................................................................................................... 101
# Table of Contents—Continued

## CHAPTER

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>101</td>
</tr>
<tr>
<td>Research Questions</td>
<td>101</td>
</tr>
<tr>
<td>Theoretical Implications</td>
<td>109</td>
</tr>
<tr>
<td>A Continuum of Students' Knowledge Structures</td>
<td>109</td>
</tr>
<tr>
<td>Three Kinds of Mental Models</td>
<td>111</td>
</tr>
<tr>
<td>The Relationship Between Concepts and Models</td>
<td>114</td>
</tr>
<tr>
<td>Future Research</td>
<td>117</td>
</tr>
<tr>
<td>Practical Implications</td>
<td>119</td>
</tr>
</tbody>
</table>

## APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Interview Script for Pilot Research</td>
<td>122</td>
</tr>
<tr>
<td>B. Electricity Survey</td>
<td>130</td>
</tr>
<tr>
<td>C. Survey Scoring Sheet</td>
<td>141</td>
</tr>
<tr>
<td>D. Informed Consent Forms</td>
<td>144</td>
</tr>
<tr>
<td>E. Protocol Clearance From the Human Subjects Institutional Review Board</td>
<td>148</td>
</tr>
</tbody>
</table>

**BIBLIOGRAPHY**                                                          | 150  |
LIST OF TABLES

1. Summary of Mental Models of Electricity as Determined by Previous Research .......................................................... 33
2. Components of a Mental Model of a Simple DC Circuit .......................................................... 39
3. Model Component #1-Nature of Electricity .............................................................................. 39
4. Model Component #2-Path of Flow .................................................................................. 40
5. Model Component #3-Mechanism of Action .......................................................................... 40
6. Model Component #4-Role of the Battery ........................................................................ 41
7. Model Component #5-Role of the Bulb ........................................................................... 41
8. Model Component #6-Role of the Wires ........................................................................... 42
9. Model Component #7-Bulbs in Series .............................................................................. 42
10. Model Component #8-Bulbs in Parallel ............................................................................. 42
11. Distribution of Groups by Grade Level ............................................................................ 54
12. Frequencies of Group 1 Responses for Model Component #1 ................................................. 57
13. Frequencies of Group 1 Responses for Model Component #2 ................................................. 57
14. Frequencies of Group 1 Responses for Model Component #3 ................................................. 58
15. Frequencies of Group 1 Responses for Model Component #4 ................................................. 58
16. Frequencies of Group 1 Responses for Model Component #5 ................................................. 59
17. Frequencies of Group 1 Responses for Model Component #6 ................................................. 59
18. Frequencies of Group 1 Responses for Model Component #7 ................................................. 60
19. Frequencies of Group 1 Responses for Model Component #8 ................................................. 60
List of Tables—Continued

20. Frequencies of Group 2 Responses for Model Component #1 .......... 65
21. Frequencies of Group 2 Responses for Model Component #2 .......... 66
22. Frequencies of Group 2 Responses for Model Component #3 .......... 66
23. Frequencies of Group 2 Responses for Model Component #4 .......... 67
24. Frequencies of Group 2 Responses for Model Component #5 .......... 67
25. Frequencies of Group 2 Responses for Model Component #6 .......... 68
26. Frequencies of Group 2 Responses for Model Component #7 .......... 68
27. Frequencies of Group 2 Responses for Model Component #8 .......... 69
28. Frequencies of Group 3 Responses for Model Component #1 .......... 72
29. Frequencies of Group 3 Responses for Model Component #2 .......... 72
30. Frequencies of Group 3 Responses for Model Component #3 .......... 73
31. Frequencies of Group 3 Responses for Model Component #4 .......... 73
32. Frequencies of Group 3 Responses for Model Component #5 .......... 74
33. Frequencies of Group 3 Responses for Model Component #6 .......... 74
34. Frequencies of Group 3 Responses for Model Component #7 .......... 75
35. Frequencies of Group 3 Responses for Model Component #8 .......... 75
36. Frequencies of Group 1, 2 & 3 Responses for Model Component #1 .... 80
37. Frequencies of Group 1, 2 & 3 Responses for Model Component #2 .... 80
38. Frequencies of Group 1, 2 & 3 Responses for Model Component #3 .... 81
39. Frequencies of Group 1, 2 & 3 Responses for Model Component #4 .... 82
40. Frequencies of Group 1, 2 & 3 Responses for Model Component #5 .... 82
List of Tables--Continued

41. Frequencies of Group 1, 2 & 3 Responses for Model Component #6....... 83
42. Frequencies of Group 1, 2 & 3 Responses for Model Component #7....... 84
43. Frequencies of Group 1, 2 & 3 Responses for Model Component #8....... 84
44. A Comparison of the Mental Models Found in Groups 1, 2 & 3 ............. 85
45. The Components of a Scientific Model ............................................. 90
46. A Summary of the Distribution of Mental Models Across Grade Levels ............................................. 91
47. Frequencies of Group 4 Responses for Model Component #1 ............. 93
48. Frequencies of Group 4 Responses for Model Component #2 ............. 94
49. Frequencies of Group 4 Responses for Model Component #3 ............. 95
50. Frequencies of Group 4 Responses for Model Component #4 ............. 96
51. Frequencies of Group 4 Responses for Model Component #5 ............. 97
52. Frequencies of Group 4 Responses for Model Component #6 ............. 98
53. Frequencies of Group 4 Responses for Model Component #7 ............. 99
54. Frequencies of Group 4 Responses for Model Component #8 ............. 99
55. Distribution of Model Types in Group 4 Across Grade Levels............. 100
CHAPTER I

INTRODUCTION

Historical Context of This Study

The issue of how students acquire and process knowledge is a fundamental question that has been under consideration for a long time by researchers in education and cognitive psychology (Brewer & Samarapungavan, 1991; Carey, 1985; Collins & Gentner, 1987; diSessa, 1983; Solomon, 1983; Wellman, 1990). Recent research in this area has focused on how students acquire knowledge about the physical world and what the structure of that knowledge looks like (Borges & Gilbert, 1999; diSessa, 1993; Sanmarti et al, 1995; Vosniadou, 1994; Vosniadou & Brewer, 1992, 1994; Vosniadou & Kempner, 1993). Historically, research on how students acquire and structure scientific knowledge has focused on (a) identifying and categorizing students' misconceptions (Clement, 1982; diSessa, 1983, 1988; McCloskey, 1983(July), 1983; Solomon, 1983), (b) describing the nature of conceptual change (Carey, 1985; Vosniadou, 1992; Vosniadou & Brewer, 1987), and (c) explaining the process by which students construct and revise mental models (Norman, 1983; Collins & Gentner, 1987; Wellman, 1990). The above mentioned research has usually been conducted by engaging students in explanatory and predictive activities in many areas of science, with a heavy emphasis on physical science.
Recently, debate has focused more specifically on how to describe students' initial, intuitive knowledge structures and on how to describe knowledge restructuring during the process of knowledge acquisition (Borges & Gilbert, 1999; diSessa, 1988; Lochhead, 1988; Vosniadou, 1994). For the purposes of this study, intuitive knowledge is described here as being knowledge that students construct of their physical and social environment based on their everyday experience. This intuitive knowledge forms the framework within which new information from instruction or direct experience is interpreted. Current arguments in the debate over how to characterize students' intuitive knowledge structures in science can be categorized as belonging to one of two sides. A brief description of these two sides follows in the next few paragraphs; a more detailed description follows in the next chapter.

Some researchers characterize students' intuitive knowledge as a "fragmented collection of ideas" that are "loosely connected" (diSessa, 1988; Lochhead, 1988; Solomon, 1983). Researchers who view students' knowledge as fragmented and nonsystematic see the process of knowledge acquisition as a process of collecting and unifying these knowledge fragments. This is usually referred to as a "knowledge in pieces" view of students' knowledge.

Other researchers characterize students' intuitive knowledge as being coherent and systematic, and that it deserves to be called a theory (Brewer & Samarapungavan, 1991; Carey, 1985; Clement; 1982; McCloskey, 1983; Wellman, 1990; Wiser & Carey, 1983). Similarly, Vosniadou & Brewer (1992, 1994) characterize this intuitive
knowledge as well-defined mental models. Researchers who think that intuitive knowledge can be described as well-defined mental models, or can be viewed as theories, see the process of knowledge acquisition as predominantly model revising or theory change.

Each of the above researchers, from both sides, has chosen to work with one or two specific areas of science (mechanics, astronomy, heat, light, etc.) as a means of studying knowledge acquisition. Many of them have mentioned that further work needs to be done in other areas of science to further describe students' intuitive knowledge structures. Consequently, the more content areas where a useful theoretical framework for characterizing student knowledge can be established, the more powerful the corresponding theory of knowledge acquisition will be. A resulting theory of learning from such research would provide both researchers and teachers a much sought after basis on which to rest claims of what constitutes "good" science teaching.

Research Questions

The fundamental assumption that this study makes is that when students acquire intuitive knowledge they initially construct well-defined, internally consistent mental models based on everyday experiences and instruction. Even though these mental models might reflect an unscientific view of the world, students use them in a way that seems logical to them when they generate explanations and make predictions. This assumption has been most recently tested in a few areas of science, namely (a)
astronomy, (b) mechanics, and (c) thermal physics (Ioannides & Vosniadou, 1991; Vosniadou & Brewer, 1992, 1994; Vosniadou & Kempner, 1993). Research on student conceptions of electricity has previously focused on describing students' misconceptions (Brna, 1988; Dupin & Joshua, 1987; McDermott & van Zee, 1984; Metiou et al., 1996; Solomon et al., 1985) or has presented conceptual models of electricity to be used to teach students (Dupin & Joshua, 1989; Gentner & Gentner, 1983; Shipstone, 1984). Shipstone (1985) and Heller and Finley (1992) took these studies one step further and described some possible mental models that students might hold that could account for some of the misconceptions researchers had documented. These possible mental models were presented based on patterns of misconceptions that researchers found, after the fact, from analyzing students' responses. However, these previous studies were not designed to expose and explore these patterns and therefore could not accurately describe any mental models that the students might be using. More recently, Stocklmayer and Treagust (1996) have documented mental models of electric current used by novices and experts. Borges and Gibert (1999) also documented mental models used by students, teachers, and practitioners.

This study will seek to demonstrate the (a) prevalence, (b) use, and (c) nature of well-defined mental models in the content area of electricity in simple DC circuits. Specifically, the research questions to be answered are:

1. To what extent can middle school students' knowledge of electricity be characterized and described using a small set of well-defined mental models and to what
extent can it be described by using a "knowledge in pieces" perspective?

2. What is the nature and structure of each of the models that middle school students possess?

3. What is the frequency and distribution of these models within the group of middle school students to be studied?

Significance

This study seeks to add to the debate outlined above by presenting evidence that this may not be an either/or question. That, in fact, it may be more fruitful to think of students' initial knowledge structures as progressing from "knowledge in pieces" to simplistic and then more complex mental models. Vosniadou & Brewer (1992, 1994) have established that students' intuitive knowledge can be characterized by well-defined mental models in the field of astronomy. Other researchers have found this characterization useful in describing students' knowledge of (a) force (Ioannides, 1991 (in Vosniadou, 1994); Ioannides & Vosniadou, 1991 (in Vosniadou, 1994); McCloskey, 1983; Clement, 1982); (b) heat (Vosniadou & Kempner, 1993; Wiser & Carey, 1983); (c) electricity (Borges & Gilbert, 1999); and (d) chemical and physical properties (Sanmarti et al., 1995). By attempting to determine the extent to which students' knowledge of electricity can also be described as one of a limited number of well-defined mental models, data from one more content area will be added to the mental models literature. As Borges and Gilbert (1999, p.99) point out:
There does seem now to be a growing consensus that, if science education is to provide more than simple knowledge of science content, that is, of specific facts and laws of science, then it must elicit how students acquire and use mental models to think of the physical world and how these models evolve with age.

Franco et al. (1999) also stress the importance and need for more research on mental models in the field of science education. They feel that the concept of mental models shows much promise in overcoming the limitations of the Alternative Conceptions Movement (ACM) that has dominated the science education literature for many years. They claim that their analysis of science education research that focused on the issue of mental models since 1986; has shown that the concept of mental models is not a mere substitution of terminology for the concept of alternative conception. This study will show how many of those alternative conceptions fit into a mental models perspective of students' knowledge.

In the content area of electricity, this study adds more depth and structure to the existing knowledge of students' conceptions of electricity. By analyzing how students use the conceptions they have constructed and how these conceptions are linked with each other, a more complete picture of students' knowledge of electricity can be developed. By using a mental models perspective to characterize students' knowledge, this picture is more useful to researchers than a list of misconceptions. By determining the degree to which students are actually using these mental models, claims both for and against some of the teaching models proposed by researchers can be evaluated.

From a teacher's perspective, this study should have a high level of practical
significance. On a more general pedagogical level, this study will provide evidence for how the two theories that characterize students' knowledge structures previously described can be reconciled with each other and how they can both inform instructional practice. How one views students' existing knowledge structures directly impacts how one views the knowledge acquisition process. As a result, this study will provide evidence as to which approach a teacher should take to teaching various topics in science.

Since this study is being carried out in the field of electricity, the results should help teachers by giving them specific information about students' knowledge in this content area. As mentioned above, previous studies have given teachers either lists of misconceptions that students have about electricity or suggested teaching models, in the form of analogies, which teachers could use to explain specific concepts. While a list of misconceptions typically held by students is more useful than having no idea what students think, its practicality diminishes as the list grows longer. Studies which propose teaching models also have some usefulness because previous studies have shown that analogies can be effective in increasing student understanding (Collins & Gentner, 1987; Gentner & Gentner, 1983). However, none of these studies have determined if students actually incorporate these analogies into their own mental models and, if so, how do students synthesize them. For a teaching model to be both useful and effective, it should help students develop more scientific models in their own minds. This study should lay the groundwork for determining which mental models middle school students use to understand electricity; and therefore, give teachers information about what to expect
from such students when teaching electricity.
CHAPTER II

REVIEW OF RELEVANT LITERATURE

Introduction

This chapter contains a review of previous research related to this study. First, a review of the mental models literature is presented to establish the theoretical basis on which this research was based. Second, a discussion of the literature concerning the nature of intuitive knowledge follows explaining different views on how students construct and organize intuitive knowledge. Third, an extensive review of the literature that describes students’ conceptions of electricity as determined in previous research is included along with a summary of that research in tabular form for comparison purposes. Lastly, a description of an informal pilot research project that was undertaken to lay the groundwork for this study is presented.

Mental Models

Gentner and Stevens' book *Mental Models* (1983) is usually cited as a seminal work in studies that take a mental models perspective. The first chapter explains that when using the construct of a mental model, one needs to consider four things: (1) the target system, or the actual system that the person is using or learning; (2) the conceptual model, which is invented by the teacher or designer to be an accurate
representation of the system; (3) the mental model of the system, created by the person who is using or learning that system; and (4) the researcher's or scientist's conceptualization of that person's mental model of the system (Norman, 1983). The chapter goes on to characterize mental models as: (a) generally incomplete but functional, (b) continually modified until workable, (c) unstable over time, (d) not having firm boundaries (ie. they can overlap), (e) frequently unscientific or superstitious, and (f) parsimonious.

Norman's distinction between conceptual models and mental models is of special significance to this study because many previous studies involving electricity have actually been describing conceptual models not mental models as described here. Conceptual models are devised as tools for the understanding or teaching of physical systems. Mental models are "what people really have in their heads" and "what guides their use and understanding of things."

Norman also uses the idea that mental models consist of concepts. These concepts reflect the person's beliefs about the system and their observations of the system. A person's mental model will be built on the concepts that describe the system and will be used to predict the behavior of the system. Norman goes on to describe the concepts that constitute the mental model as forming descriptive, explanatory and predictive parts of the model. Each of these parts can be utilized, together or separately, to engage in descriptive, explanatory and predictive activities.

Franco et al. (1999) also describe mental models as consisting of concepts and
that the concepts are the ‘pieces of knowledge’ that diSessa (1988) describes. They see descriptions of mental models as being based on descriptions of the connections between concepts. In other words, describing a network of connected concepts would be an effective way to describe a person’s mental model.

An example of this viewpoint of mental models can be found in the area of forces and motion. It has been widely reported in previous research that a common conception held by students is that force is something that a moving object possesses. Another common and related conception is that force is something that can be transferred from one object to another. A third related conception explains that an object can be made to move by having another moving object transfer some of its force to the stationary object causing it to move. The first two concepts are mostly descriptive in nature and the third one is more explanatory since it involves a cause and effect relationship.

These three concepts could be connected together as model components to become part of a person’s mental model that they construct when they see someone throw a ball into the air. They could then use that mental model to give an explanation of this situation that might be similar to this:

1. The hand transfers force to the ball as it is being thrown.
2. The ball continues to move upward after it leaves the hand because of the force it now possesses.
3. The ball slows down as it runs out of force.
4. The ball falls back to the ground because it has no more force left.
The person could use these same concepts as model components to engage in other descriptive, explanatory, or predictive activities such as: (a) describing the role of a bat hitting a baseball, (b) explaining the interaction between a bowling ball and pins, or (c) predicting what will happen when two different size rocks are thrown into the air.

Gentner & Gentner (1983) explain the use of analogy in the formation of mental models. They use the content area of electricity to explore the role of analogy. Two conceptual models are discussed, the water-flow analogy and the moving-crowd analogy. These analogies are commonly used as conceptual models to teach electricity to students with the expectation that they will incorporate these analogies into their own mental models. Neither analogy serves as a complete representation of electricity because the water-analogy works well to describe the behavior of batteries but not resistors and the moving-crowd analogy can describe resistors but not batteries.

Upon testing students who seemed to have mental models and that used one analogy or the other, the researchers found that they performed as predicted on battery/resistor problems. Students with a flowing water mental model of electricity did better on battery problems and students with a teeming crowd mental model of electricity did better on resistor problems. This research provided more evidence that: (a) students do construct mental models; (b) that those mental models are influenced by the use of conceptual models, specifically analogies; and that (c) it is possible to determine the nature of a student's mental model by analyzing their performance on certain tasks. These findings were also reported by Collins & Gentner (1987) by using analogies to
influence the mental models that students construct concerning evaporation.

More recently, Vosniadou & Brewer (1992, 1994) use the construct of a mental model to describe students' intuitive knowledge of astronomy. In their research, a mental model refers to a kind of mental representation that is an analog representation of what is actually being observed. Vosniadou (1994) goes on to explain that, from her point of view:

1. Mental models are generated during cognitive functioning to preserve the structure of that which they represent.

2. Mental models are dynamic and generative representations which can be manipulated mentally to provide causal explanations and make predictions of physical phenomena.

3. Mental models are, for the most part, partially created on the spot from existing knowledge structures to deal with the demands of a specific problem and situation.

4. Mental models, which have proven useful in the past, may be stored, as a whole or in parts, as separate cognitive structures and retrieved from long-term memory as needed.

5. Mental models, whether generated or retrieved during cognitive functioning, are the points at which new information is incorporated into the knowledge base.

6. Mental models can constrain the knowledge acquisition process in ways similar to beliefs and presuppositions.

7. Mental models can provide information about the underlying knowledge
structures (concepts, partial models, beliefs, etc.) from which they are generated.

8. Mental models are internally coherent structures that can be inferred from the consistent explanations generated by students who use these structures.

These characteristics of mental models describe how this construct will be used throughout this research. Mental models are described as being, as a whole or in part, descriptive, explanatory, and/or predictive. These aspects of the model can be determined by engaging students in descriptive, explanatory and predictive activities. The models are also characterized as possessing a number of specific model components that are linked together in specific ways. The descriptions of each of the model components can be generated by using students conceptions and beliefs about the circuits and their parts that they were describing. The logical consistency within students’ explanations can be used as the primary evidence for the existence of an internally coherent structure, namely a mental model.

Using internal logical consistency as evidence for the existence and use of mental models is what distinguishes this study from previous studies on students’ knowledge of electricity. Vosniadou & Brewer (1994, p.176) point out that:

In most of the existing research where such inconsistencies are noted, a student is considered to be internally inconsistent if he or she uses a given scientific concept correctly in some cases but not in others. The possibility that this student is using a representation which is different from a scientific one, but which is nevertheless well-defined and internally consistent and which can account for the obtained pattern of ‘correct’ and ‘erroneous’ responses, is usually not explored in a systematic fashion.

In the current study, students’ apparent inconsistencies were analyzed to see if
they could be explained by the consistent use of an unscientific concept. If students used a set of concepts consistently and logically throughout their explanations, even if the concepts were unscientific in nature, they were assumed to have a mental model. Students who switched and used different conceptions to explain similar questions were assumed to have an incomplete or mixed mental model depending on their level and type of inconsistencies. Students who demonstrated little or no consistency could be viewed as having no mental model or an undetermined mental model depending on one's perspective. Vosniadou & Brewer (1992, 1994) chose to use the latter designation.

Consistency is only part of the criteria used for this type of analysis. Vosniadou & Brewer (1992, 1994) use internal logical consistency as a more stringent criteria. Within the set of explanations given by the student, there should exist no obvious contradictions between the concepts being used by the student. For example, a student who said that the earth was round like a ball and then later maintained that if you walked far enough you would fall off the edge of the earth; would be considered contradictory, or illogical, no matter how consistently they used those explanations. Now if they said that you would fall off if you walked to the bottom because you would be upside-down, then that would be logical, although unscientific, given their concept of the shape of the earth. Students who exhibited this type of illogical thinking were also considered to have incomplete or mixed mental models depending on the level and type of logical inconsistencies. Students who demonstrated little or no logical consistency could be viewed as having no mental model or an undetermined mental model depending on one's
perspective. Again, as in the previous criteria, Vosniadou & Brewer (1992, 1994) chose to use the latter designation.

Intuitive Knowledge

Knowledge in Pieces

DiSessa's view (1983, 1988, 1993) of intuitive knowledge acquisition is representative of the 'fragmented knowledge' model of nonscientific reasoning. He claims that intuitive knowledge in physics consists of a large number of fragments instead of one or even a small number of integrated structures that might be called 'theories'. He refers to these fragments as 'p-prims', short for phenomenological primitives, and describes them as "simple abstractions from common experiences." These p-prims are considered primitive in the sense that they generally need no explanation, they simply happen.

As an example, diSessa presents the 'more effort begets more results' p-prim. He claims that students possess no explanation for this phenomena and that, from the student's perspective, one is not needed. Because students have so much experience with things that work this way, it becomes encoded as an expected event. DiSessa presents an exhaustive list of p-prims (1993) that can be used to analyze students' explanations. He claims the ability to decompose students' explanations into a set of plausible p-prims is one piece of evidence that undermines the 'theory theorists', those that claim students' knowledge can be characterized as structures which are theory-like.
His second, and he claims, most compelling piece of evidence is that when one analyzes subjects' responses to problem situations in mechanics, one finds that they give multiple kinds of predictions and explanations (diSessa, 1988). None of the subjects gave a purely 'impetus-like' or Aristotelian explanation as some of the 'theory theory' researchers had claimed they would (McCloskey, 1983 (July)). He explained the variability in the subjects' explanations as evidence that they were all using their own p-prims to generate these explanations. He concludes by stating, "...perhaps the most fundamental problem is the simple fact that students come to physics classes with no theory at all, but instead are used to dealing with the world on a catch-as-catch-can basis..." (diSessa, 1988, p.52).

Knowledge as Mental Models

Vosniadou and Brewer represent the other side of the 'theory of knowledge acquisition' debate. They use the term intuitive knowledge to describe knowledge that students have obtained by developing an understanding of the world around them based on their everyday experience (Vosniadou & Brewer, 1992, 1994). While diSessa theorized that students' intuitive knowledge was accumulated in unconnected or poorly connected pieces, Vosniadou and Brewer maintain that students synthesize information they receive into coherent mental models which they use in a consistent fashion to explain the world around them and make predictions.

Vosniadou and Brewer point out that it is easy to conclude that students'
knowledge is fragmented because they make seemingly contradictory and inconsistent statements about the world around them. But, what may appear to be contradictory and inconsistent to an adult or expert may not be so from the point of view of the child or novice. They support this by carefully analyzing the responses of many children to questions about the shape of the earth (Vosniadou & Brewer, 1992). From these responses, and the literature on previous research describing children's misconceptions of the earth, they described seven mental models of the earth that the children seem to hold. When the children's responses were viewed from the point of view of these models, 80% of the children in the study were found to be giving answers that matched only one of the models developed, on a consistent basis.

This study also revealed that about 10% of the students gave inconsistent responses that fit none of the theorized models and the researchers were not able to construct additional models that would account for these peculiar answers. Vosniadou and Brewer also found another 10% who had what they termed mixed models. These students were inconsistent because they seemed to be switching back and forth between two or more of the established mental models. These students could be viewed as being in transition between models and could possibly be engaged in model and/or theory revising as they answered. This transitionary stage was reflected in their answers and resulted in inconsistent and contradictory responses.

Vosniadou & Brewer's follow up study (1994) described students' mental models of the day/night cycle. In this study, the mental models were more complex than in the
previous study. A mental model of the day/night cycle was characterized as being made up of four components:

1. Explanations of the disappearance of the sun at night.
2. Explanations of the movement of the moon.
3. Explanations of the disappearance of the stars during the day.
4. Explanations of the changes from day into night and back again.

Student's were asked a series of questions to elicit explanations in all four of these areas. Student's explanations were categorized by similar type for each component. Descriptions of students' underlying mental models were generated by combining the type of explanation used from each of the four components. This produced 12 different mental models, 3 mixed or incomplete models and one category of students whose mental models were deemed undetermined by the researchers. Since the number of explanation types for each component varied from 8 to 12, the number of possible combinations of explanations from four different components could conceivably generate a huge number of possible mental models. However, 68% of the students' explanations could be characterized as belonging to one of 12 mental models, 27% were characterized as having mixed models and 5% fit none of the models. This decrease in percent of students' explanations that could be characterized by mental models from the first study is understandable given the increase in complexity from one model component to four.

These two studies, Vosniadou & Brewer (1992, 1994), provide the theoretical and
methodological basis for this study. It was hypothesized that it would be possible to analyze students' descriptions and predictions of simple DC circuits and then categorize many of those responses as belonging to one of a small set of possible mental models and that those mental models would be internally logically consistent, albeit unscientific. This would demonstrate that, like astronomy, many students' possess an intuitive knowledge of electricity can be characterized as being in the form of mental models or 'theory-like'. It was also assumed that, like astronomy, there would be some students whose knowledge of electricity could not be characterized this way; and could be viewed as either mixed, incomplete or undetermined mental models or even a collection of unconnected pieces.

Student Conceptions of Electricity

McDermott and van Zee (1984) describe one unscientific model of electricity. They found students who refer to 'something' in the circuit that gets used up by the bulb. Students use the terms current, energy, power, potential difference, and voltage to describe this 'something', sometimes they use these terms interchangeably. The students also seemed to believe that the same amount of this 'something' was supplied by a battery to all circuits. Since this 'something' was used up by the bulbs, the direction of the flow was important as it determined which bulb would be first in the flow, and therefore the brightest.

Shipstone (1984, 1985) was one of the earliest studies to attempt to explain
students explanations of electric circuits by grouping them into what he called ‘conceptual models’. His models tended to focus on students conceptions of flow and energy usage. Shipstone also found that students used many different terms to refer to ‘electricity’, with current being one of them. He used the term current throughout his descriptions of students' mental models just as a convenience, not as a scientific term. He points out that once students are introduced to the term current they tend to use it, but continue to just mean 'electricity' in general. Shipstone's five conceptual models that describe the way students represent the phenomena that occur in DC circuits are described below:

1. Unipolar model - Current travels from one terminal of the battery only and all of it is used up by the bulb. Therefore, only one wire is needed from the battery to the bulb. The other wire(s) may be necessary but plays a passive role, with no current travelling through it.

2. Clashing Currents model - Current leaves the battery through both terminals and is used up by the bulb(s).

3. Attenuation model - Current travels through the circuit in one direction only. More current leaves one terminal than returns to the other. This model leads to the conclusion that in a series of bulbs the first bulb gets the most electricity and the last bulb gets the least electricity.

4. Sharing model - In this model the current leaves one end of the battery and flows through the bulbs getting used up by each bulb in the process. It is like the
attenuation model but in this case, the current is equally shared by all bulbs. This would imply some type of feedback mechanism or communication between the bulbs to somehow insure the equal allocation of electricity, but that mechanism is not addressed in this model.

5. Scientific model - Current travels in one direction in the circuit and is conserved. The energy provided by the battery (voltage) is what gets used up by the bulbs. The amount of energy used up by each bulb is determined by the amount of current that can flow through it.

Shipstone reports several instances of students engaging in model-switching among models 1-4 described above, while attempting to explain different situations. This could imply that there existed other models which were a hybrid of two of the models which he described. Shipstone also found that 12-year-olds preferred the attenuation model and the clashing current models over the other models. He points out that his study would not have detected the Unipolar model with certainty because of the types of problems used in the survey; few used one wire connecting the battery with the bulb, most used complete circuits. This makes it clear that future research should allow for students with a Unipolar view to answer questions without getting any visual or verbal cues that contradict this view.

He further states that the clashing currents model is the one usually referred to by children once they become aware of the presence and/or need for a second wire. This shows that the clashing currents view is a result of model revision incorporating
experiential knowledge into a Unipolar view. It would be logical to assume then that, due to the nature of the problems presented in his survey, most of the students possessing Unipolar models would have used a clashing currents model instead since there were few, if any, Unipolar problems provided.

The study then tracked the prevalence and usage of the five models described above through 17 year olds. Shipstone found a steady increase in the use of the scientific model so that by 17 a majority had adopted it. He also found a steady decrease in the other models so that by 17, almost none of the subjects used the clashing currents models, few used the sharing models, and almost 40% used the attenuation model. While the attenuation model showed a steady and significant decrease in usage as the age of the subjects increased, it still was remarkably persistent. Shipstone again points out that one of the most difficult problems in attempting to classify students' responses was uncertainty over the meanings of the terms they were using. Most use these scientific terms as vague synonyms for 'electricity', others use them to mean different aspects of electricity; but exactly what they mean is not clear from the research done so far.

Another difficulty Shipstone encountered involved the type of light bulbs used in the study. He points out that when previous researchers had used standard flashlight bulbs, students were much more likely to give unipolar-model type answers. He found that students saw the metal threads on the base of the bulb as merely serving a support function to attach it to a base. They saw the small nipple at the bottom as the actual electrical contact. Most students did not assign a dual purpose to the threaded base, both
as an electrical contact and the means to secure it to the base. Shipstone suggested that further studies utilize bulbs in such a way so as to make it obvious to students that a bulb has two electrical contacts. He presented evidence that in studies where a tubular 'festoon' bulb was used, with contacts on both ends, students were much less likely to be misled by the bulb's appearance. Shipstone also points out that students who already held a scientific model were also misled by the bulb's appearance. These findings are also incorporated in this proposed study. Students will be shown bulbs that are already mounted in bulb holders that have two contacts on them.

Lastly, Shipstone presents another possible model that some students might hold concerning electrical circuits. He refers to this model as the sequence model, although it has been used in other studies under different names. At first it appears to be just like the attenuation model, but upon further study one can see an increase in complexity that distinguishes it from its cousin. While the attenuation model uses a unidirectional current that gets used up bit by bit as it passes through various parts of the circuit; the sequence model further posits that devices in the circuit that are located further along in the sequence do not affect devices that the current encounters first. This is also different from the sharing model, which was not discussed very much in this study, in that the sharing model implies that all devices do have an effect on each other no matter what their position in the sequence.

Shipstone further shows that there is a relationship between students who use the attenuation model and also invoke the sequence model for more complex circuits. He
draws a relationship between students who do not use the attenuation model and subsequently do not use a sequence model for more complex circuits. The factor that most influences which of the two closely related models students will use, seems to be the complexity of the circuit. Obviously if a circuit only contains one device a student will not attempt to explain it using a more complex sequence model when the attenuation model will suffice. Maybe they really are the same mental model, with only some parts being put to use in simple problem solving tasks and other parts being put to use in complex tasks. Shipstone (1984, p. 80) concludes with the following assertion:

...it is not the case that children normally commence their studies with a firm conviction about the validity of any of the detailed models described, most do begin with a source-consumer view which they hold very tenaciously, though its exact form may vary over time and from situation to situation. At a detailed level there are probably few pupils who will attempt to apply any one principle, valid or not, in general. Despite the evidence for model-switching the models do provide a useful guide to the main lines that pupils might follow in their reasoning.

Solomon et al (1985) focused more on the nature of electricity itself then on its behavior in a circuit. They studied 11-12 year olds who had not studied electricity in school and 13-14 year olds who had completed a unit on electricity. They found that there was more variation within classes than there was between age groups. The only exception to this was that significantly more of the older students thought that electricity was "like a river" than did the younger students. The most common answers for both groups were "electricity is like a dangerous animal" and "electricity is like a fuel." The least used analogy was that "electricity was like a lot of tiny particles." These conceptions of electricity were not included in Shipstone's models. However, they need
to be considered in a comprehensive mental model of electricity because a student's view of the nature of electricity will provide the basis for their mental image of how it flows. Such will be the case in this study.

Dupin and Joshua (1987) studied 920 French students from sixth grade up to the fourth year of university, ages 12-22 years. Using a pencil and paper test, they tried to identify the students' conceptions of electricity in DC circuits involving batteries and bulbs. While this study focused more on students' confusion over current and potential difference than the other studies, it did uncover some of the same misconceptions as previous studies. Dupin and Joshua reported that (a) a majority of students up to grade 8 held a current wearing-out model, (b) the number of students incorporating the moving-fluid metaphor into their explanations increased with age, and (c) that the battery delivers a constant current no matter what circuit it was part of was held by a majority of students at all levels. They also found that potential difference was fundamentally misunderstood by the subjects.

Brna (1988) studied misconceptions in basic electrical theory using volunteers from an all boys school whose student body is considered well above average. The subjects' ages were not given but they appear to be high school age. Brna reported finding evidence of misconceptions about the battery providing a constant current and that the current is consumed as it goes around the circuit. He also reported no evidence of the clashing currents model that Shipstone described. Brna also listed many other general misconceptions but these focused mainly on students' mistakes concerning the
concepts of current, potential difference, power and topology of circuits. Because explanations of the answers to the misconceptions test Brna administered were not presented, it is not possible to incorporate many of his findings into the models from previous studies discussed.

Heller and Finley (1992) proposed two basic models of electricity and electric circuits to describe elementary school teachers' knowledge of these content areas. They also described some variations on these two basic models since some subjects did not consistently use one of the proposed models to solve all of the problems presented to them. This would lead one to believe that there could have been more than two mental models constructed by the subjects, with some being similar to each other.

Heller and Finley (1992) found that all subjects used the term current in their explanations but used it to mean energy. They did not address whether the subjects thought of this current/energy as a substance (fluid or particulate) or as an entity totally lacking substance but still able to make the bulbs light, which is the scientific conception of energy. They also found that all subjects believed that the battery was the source of this current/energy and that the wires in the circuit were empty of the "stuff" that flows through them. This seems to indicate a fluid-like substance conception of the nature of this current/energy coming from the battery. Almost all subjects held the notion that the battery releases the same, fixed amount of this current/energy to every circuit. From here, the researchers developed two conceptual models that they felt described the subjects' causal models that explained how the electricity behaved in different circuits.
One they called the 'static' model. It describes electricity as current/energy that is equally dispersed throughout the wires to all the bulbs in a circuit, and that all bulbs in a circuit are the same brightness because they each receive the same amount of current/energy. This type of model could be indicative of a pure energy or field conception of the nature of electricity because it seems to imply that electricity can be everywhere at once. Whether or not this is the case, the researchers do not say. This model was only found in one subject with no further data presented as to the nature of this subject's knowledge.

The other model they called the 'sequential' (or dynamic) model. This was the most commonly held model among the subjects. This model describes electricity as current/energy that flows out of the battery and does not decrease until it reaches a bulb, or some other circuit element, which uses up some of the current. A bulb's brightness is dependent on how much current/energy flows to the bulb. When there is more than one bulb in the circuit, each bulb uses up some of the current/energy, so all bulbs receive less. This model seems to reflect a fluid-like conception of the nature of electricity.

The researchers also described two other subjects that did not fit in these categories. One did not seem to have a complete model but did consistently invoke a rule that the farther away the bulb is from the battery, the dimmer the bulb. The subject did not have an explanation or a causal model for this rule but he did use it consistently. This incomplete model does reflect a fluid-like, dynamic view of electricity.

Other subjects, from the sequential model group, also invoked this distance rule
in their explanations but they further provided the explanation that the wires use up some of the current/energy. Some of the sequential model subjects did not use this rule and simply described the wires as conducting the current/energy with no effect at all. This division might be indicative of an important distinction between two types of sequential models. One that is almost water-like, where the electricity can flow freely like water through pipes without getting used up; and one where the electricity does somehow interact with the wires and may be more energy-like (or possibly particulate) in how it gets transferred through the wire. One final subject seemed to have no model at all. The researchers described his knowledge as "random fragments". This subject gave inconsistent answers to the problems.

In describing variations of the sequential model, the researchers also uncovered some other conceptions of electricity. Two subjects believed that the current/energy flows from both ends of the battery. The others said that it flows out of one end and in to the other, some from negative to positive and some from positive to negative. One of the dual-flow subjects was also the incomplete model subject mentioned above. The other was a sequential model subject who also thought that the wires do not interact with the electricity they are just there to let it flow.

The final conception that the researchers described was a description of what happens to this current/energy when it reaches a junction in the circuit. There was a high degree of variability here with half of the subjects generating explanations that involved the division of the current/energy and half did not utilize the division of the
current/energy. The researchers did not try to compare the nature of these explanations with each subject’s previous responses. The only commonality was that these subjects were all placed in the general sequential model category.

One explanation of the subjects’ considerable variability to this last problem is by inferring that they do not all possess the same mental model of electricity and electric circuits. The researchers tried to explain the variability by assuming that it was a result of some subjects switching to the static model and other subjects changing their sequential model. However, since we do not know what types of responses a typical static model subject would generate we can not be sure that this is true. As to subjects changing their initial models, that may be true; but since we do not have an accurate representation of each of the subject’s initial models, we cannot know if they were changing models or were applying slightly different initial models to the same problem.

Metiouï et al. (1996) also made reference to and noted the existence of the ‘unipolar’ model, the ‘clashing currents’ model, the ‘attenuation’ model, the ‘sharing’ model, and the ‘sequential’ model. Their study went on to examine students’ misconceptions of Ohm’s law, voltage, current, and resistance. It did not add any new information concerning students mental models of electric circuits.

Borges & Gilbert (1999) is a study very similar in purpose to this research with a less structured methodology. Their attempt was to use the concept of mental models, as a theoretical basis, and to describe the mental models of simple DC circuits held by various subjects. One major distinction of this study from previous work was the
researchers description of what a mental model of electricity might look like. They identified seven aspects or components of a mental model of electricity. The seven components were:

1. A conception of the differences between current, energy, and electricity.
2. The polarity (bi- or uni-) of the battery.
3. The existence and type of path for the electricity to follow.
4. What gets used in an electrical device?
5. How does the electricity get used?
6. A description of how the electricity circulates.
7. The nature of electricity.

Borges & Gilbert also found that each of the previous studies provided information on only some of those components. However, in their review of research they did identify the same models as described above as being evident in the data presented.

Borges & Gilbert used an unstructured interview with (a) students, (b) physics teachers, (c) electrical engineers, and (d) electricians with no formal instruction in the science of electricity. The interview involved asking questions about simple circuits that involved prediction, observation, and explanation. The subjects also used batteries and bulbs to make the circuits they described and discussed their thinking as they tried to make the bulbs light. The transcripts were reviewed for anecdotal evidence of the types of mental models that the subjects seemed to be using. Four different models were found
which were similar to the models already discussed here: (1) electricity as flow, (2)
electricity as opposing currents, (3) electricity as moving charges, and (4) electricity as
a field phenomenon. The researchers pointed out that the differences they did find in
their models were most likely due to the fact that they used a wider range of subjects;
from young novices to older, more experienced, experts.

Another interesting result, similar to Vosniadou & Brewer’s (1992, 1994) results,
was the evidence of mixed models at all levels. Borges & Gilbert also found subjects
whose responses appeared fragmented and it was not possible to assign them to a model.
The distribution of models showed that novices used models that were the least scientific
or initial models, which are not influenced by instruction but based on observation and
experience. The experts used the more scientific models involving the conceptions of
moving charges and electrical fields. According to Borges & Gilbert, this distribution
suggests a rough progression from simple phenomenological models up to the culturally
accepted scientific models.

Summary of Previous Research

All of these results are summarized in Table 1. Within the previous research, six
distinct general models of electric circuits were found. These descriptions are organized
into six different rows that correspond to different aspects or components of the model.
Some models are incomplete and are indicated by a ‘?’ because no data was presented
in these studies that would provided insight into how someone using that particular
### Table 1

**Summary of Mental Models of Electricity as Determined by Previous Research**

<table>
<thead>
<tr>
<th>Model Component s</th>
<th>The Unipolar Model (^{1,3,5,6,7,8,9})</th>
<th>Clashing Currents Model (^{1,5,7,8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) The nature of electricity</td>
<td>Electricity flows as a fluid-like substance. Usually referred to as 'current'. 'Current' and energy are thought of as the same thing.</td>
<td>Electricity flows as energy or 'current'. Electricity is composed of two different kinds of energy that are opposites of each other.</td>
</tr>
<tr>
<td>B) Description of electricity flow</td>
<td>'Current' flows through wire as if it were a hollow, empty pipe. Only one wire is needed to transport current from battery to the bulb. 'Current' flow is a one-way trip. 'Current' does not interact with wire. Second wire plays no role or is used to carry away by-products of bulb as it uses up current (ie. exhaust). But this is not needed.</td>
<td>2 wires are needed. The 2 different energies flow out of both ends of the battery. No interaction with wires, energy just passes through the wire. Energy flow is a one-way trip but from two different points.</td>
</tr>
<tr>
<td>C) Electricity usage</td>
<td>'Current' gets used up by bulb and turned into light &amp; heat, almost like a fuel.</td>
<td>2 energies meet at bulb and combine to form light and heat. Both energies get used up.</td>
</tr>
<tr>
<td>D) Explanation of battery</td>
<td>Battery is source of this 'current' that flows from one end of the battery to the bulb. When it is used up (empty), battery is dead. 'Current' can flow out both ends of the battery but second wire is not necessary. If two wires are used bulb might burn brighter or battery might run out faster.</td>
<td>Battery is source of both 'currents'. When they are used up, battery is dead.</td>
</tr>
<tr>
<td>E) 2 bulbs in series</td>
<td>Each uses up some of the 'current'.</td>
<td>?</td>
</tr>
<tr>
<td>F) 2 bulbs in parallel</td>
<td>?</td>
<td>+ &amp; - energy splits at junction with half going to each bulb. Both are dimmer than a single bulb because each gets half the energy.</td>
</tr>
<tr>
<td>Model Componen ts</td>
<td>Current Consumption Model</td>
<td>Constant Current Model</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>A) The nature of electricity</td>
<td>Electricity flows as a fluid-like substance. Usually referred to as 'current'. 'Current' and energy are thought of as the same thing.</td>
<td>Electricity flows in a fluid-like way (may or may not be a fluid-like substance), is usually referred to as 'current'. It contains energy as it flows.</td>
</tr>
<tr>
<td>B) Description of electricity flow</td>
<td>'Current' must flow in a round trip path out one end of the battery, through wires and bulbs and into the other end of the battery. 2 wires are required for bulb to light. Wires are thought of as empty pipes until connected to battery. 'Current' does not interact with wires.</td>
<td>Electricity flows through the wires and does interact with them. As it rubs against the material in narrow passages, energy is formed. Wires may be thought of as empty of the 'stuff' of electricity until connected to the battery. Energy circulates with the 'current'. Energy is transmitted to the bulb (one-way) but the 'current' circulates (round-trip) so two wires are needed.</td>
</tr>
<tr>
<td>C) Electricity usage</td>
<td>Some 'current' gets used up by the bulb, like the Unipolar Model, and the rest returns to the battery.</td>
<td>Bulbs use the energy from the 'current' to produce light and heat. The 'current' is not used up but returns to the battery.</td>
</tr>
<tr>
<td>D) Explanation of battery</td>
<td>Battery is the source of this 'current' that flows out one end, through the circuit, and into the other end. When it is used up (empty), battery is dead.</td>
<td>Battery supplies energy (and possibly 'current' too?). 'Current' flows out one end and in the other.</td>
</tr>
<tr>
<td>E) 2 bulbs in series</td>
<td>(Same as Unipolar Model)</td>
<td>Each uses up some of the energy.</td>
</tr>
<tr>
<td>F) 2 bulbs in parallel</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Model Component</td>
<td>Static or Field Model 1,5</td>
<td>Moving Crowd Model 1,4,5,7,8,10</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>A) The nature of electricity</td>
<td>Electricity is energy that is equally dispersed everywhere in the circuit at the same time.</td>
<td>Electricity is energy carried by moving particles.</td>
</tr>
<tr>
<td>B) Description of electricity flow</td>
<td>Electricity instantly fills wires with energy that is the same everywhere.</td>
<td>The particles travel through the metal in the wires carrying the energy. They squeeze through the molecules in the wires. These particles may already be in the wires with more particles and energy coming from the battery. 2 wires are needed so that the particles can return to the battery and get more energy.</td>
</tr>
<tr>
<td>C) Electricity usage</td>
<td>The bulbs use this energy and produce light &amp; heat.</td>
<td>Particles give energy to the bulb as they move through the bulb. The harder it is to get through the bulb, the more energy the particle will give off but fewer particles will be able to get through at a time. This energy is given off by the bulb as light and heat.</td>
</tr>
<tr>
<td>D) Explanation of the battery</td>
<td>The battery releases the same amount of energy to all parts of the circuit. When it runs out of energy it's dead.</td>
<td>Battery provides energy to the particles and makes the particles move in one direction. When one particle leaves the battery another enters the other end.</td>
</tr>
<tr>
<td>E) 2 bulbs in series</td>
<td>All bulbs the same brightness because energy is the same everywhere.</td>
<td>Identical bulbs will have the same brightness but be dimmer than a single bulb. Particles give some energy to one bulb as they pass through and some more to the next bulb according to how many particles the bulb will let through.</td>
</tr>
</tbody>
</table>
Table 1—Continued

*Superscripts refer to the following references: 1 Borges & Gilbert, 1999; 2 Brna, 1988; 3 Dupin & Joshua, 1987; 4 Gentner & Gentner, 1983; 5 Heller & Finley, 1992; 6 McDermott & van Zee, 1984; 7 Metiouï et al., 1996; 8 Shipstone, 1984, 1985; 9 Solomon et al., 1985; 10 Stocklmayer & Treagust, 1996

model would describe that component.

Pilot Research

Based on the results of the literature review a series of informal interviews were conducted, similar to Borges & Gilbert (1999), with approximately 20 middle school students (See Appendix A for a copy of the interview script). The interviews were conducted to find evidence of any of the described models in Table 1 or their components. The interview questions were specifically designed to elicit explanations of each of the previously described model components. Furthermore, because the interviews were informal and unstructured enough to allow students to give extensive descriptions and explanations; more detail was provided as to the nature of these components. Students were interviewed one at a time for 30-40 minutes. They were asked to describe what they knew about: (a) what a battery does and how it works, (b) a light bulb and how it works, (c) a wire and how it works, and (d) what electricity is and what it might look like.

The students were then shown diagrams of incomplete circuits (See Appendix A) and asked to predict if they would light up and to explain their predictions. If a student
said that an incomplete circuit would light then they were shown all the diagrams of incomplete circuits before being shown diagrams of complete circuits. This was done to keep from giving students cues as to which were the correct circuits and which weren’t. If students correctly stated that the incomplete circuit would not light, and explained why, then they were shown diagrams of complete circuits mixed in with incomplete circuits. When students stated that a drawing would not work, they were asked to fix the drawing by drawing on it to make the circuit work. They were also asked to explain their diagrams and elaborate on what they thought was happening inside the wires, the battery and the bulb.

Any terminology, scientific or otherwise, that students used was directed back to the student for explanation in the form of a question, like “What did you mean by ____?” Students were not given any feedback as to the correctness of their answers or allowed to test which circuits would work. Every attempt was made to get as much explanation as possible concerning what they already knew without engaging in any problem solving or cognitive conflict.

While none of the students exhibited evidence of all the components from any one model contained in Table 1, most of the individual components were evident in their explanations. The interviews provided a more detailed explanation of the different model components than was available from the previous research. The interviews also provided some much needed insight as to which questions were more fruitful at generating useful student responses for each type of model component. Many of these questions were
utilized, with some revision, in the final instrument that was designed for measuring students' knowledge of electricity for this study.

It was found from the interviews that students' descriptions could be broken down into eight categories or model components with many of the students using one description, explanation, or prediction consistently for each of the eight components. Some students used two different descriptions, explanations or predictions for a specific component during the course of the interview. This showed that some students, similar to what Vosniadou & Brewer (1992, 1994) found, were more internally consistent in their explanations than others. This consistency, and lack thereof, in students' explanations indicated the possible existence of mental models in some students but not in others. As a result of these interviews, the more formal design that makes up this study was undertaken to determine just what those models could be and to determine how prevalent they were.

Not only did the information gathered from the interviews duplicate many of the same explanations found in the previous research, it also led to a more detailed breakdown of the model components found in Table 1. Consequently, this study focused on the eight components that are believed to be necessary for a complete description of a student's mental model of a simple DC circuit as shown in Table 2.

For each of the components in Table 2 a list of predicted responses was developed. These are shown in Tables 3-10. These tables represent a comprehensive list of predicted responses students might give to questions in each model component.
Table 2

Components of a Mental Model of a Simple DC Circuit

<table>
<thead>
<tr>
<th>Model Component</th>
<th>Focusing Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>What is electricity?</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>How does electricity flow?</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>How does electricity work?</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>How does a battery work?</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>How does a bulb work?</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>How does electricity get through the wires?</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Which bulb will be brighter?</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Which bulb will be brighter?</td>
</tr>
</tbody>
</table>

Table 3

Model Component #1-Nature of Electricity

What is Electricity?

| 1) Electricity is a fluid (liquid or gas). | 2) Electricity is pure energy, not a substance, like light or heat. | 3) Electricity is moving particles. | 4) Electricity is carried by moving particles.* |

category. These responses were generated from the data presented in previous research and from the types of responses given in the pilot interviews. Responses marked with an asterisk (*) are considered to be the most scientific response in the set for a middle school student.

Table 8 actually contains 3 subsets of responses within the set of predicted responses. The first subset contains responses describing the nature of the wires. The
Table 4

Model Component #2-Path of Flow

How Does Electricity Flow?

| 1) Flows in one direction only from one end of the battery, a one-way trip. | 2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires. | 3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other. | 4) Round trip flow in one direction, both wires needed. Out one end of the battery and in the other end. Electricity only makes the trip once.* |

Table 5

Model Component #3-Mechanism of Action

How Does Electricity Work?

| 1) Electricity flows from the battery to the device and is used up. | 2) Electricity has two parts, (+ & -), both come from battery and combine in device to make it work. Both are used up. | 3) Electricity flows to device where some of its energy is used up, it then flows back to the battery. | 4) Electricity flows to the device and gives off all its energy then flows back to the battery. | 5) Electricity flows to the device and reacts, may be changed into something else. |

second subset contains responses describing whether wires contain the ‘stuff that flows’ before they are hooked to the battery. The third subset contains responses describing whether it takes energy for the electricity to get through the wires. The subsets are separated by a bold line.
Table 6

Model Component #4-Role of the Battery

How Does a Battery Work?

| 1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank. | 2) Active – is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out. | 3) Active – only pushes electricity around, pump-like, when it is unable to push the electricity it is dead. | 4) Active – it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge it is dead. | 5) Active – produces electricity inside it. When it is no longer able to produce it, it is dead. Battery forces electricity out.* |

Table 7

Model Component #5-Role of the Bulb

How Does a Bulb Work?

| 1) Electricity is released by the wires in the bulb causing light. | 2) Both types of electricity, (+ & -), combine in bulb and react or explode causing light and heat. | 3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products). | 4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.* |

Summary

In summary, this study attempts to describe most middle school students' knowledge of simple DC circuits as being well-defined, internally consistent mental models, and that students whose knowledge cannot be described that way possess
### Table 8

Model Component #6 - Role of the Wires

How Does Electricity get Through the Wires?

<table>
<thead>
<tr>
<th>1) Lets electricity flow through like tubes.</th>
<th>2) Electricity flows on the outside of the wire, inside the insulation.</th>
<th>3) Electricity flows through spaces in the wire.</th>
<th>4) Electricity flows from molecule to molecule in the wire.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>2) Wires already contain the stuff that flows.*</td>
<td>1) It takes energy to get through the wires.*</td>
<td>2) It doesn’t take energy to get through the wires.</td>
</tr>
</tbody>
</table>

### Table 9

Model Component #7 - Bulbs in Series

Which Bulb Will be Brighter?

<table>
<thead>
<tr>
<th>1) Won’t work because they must be hooked to battery separately.</th>
<th>2) Both the same as each other and the same as the single bulb.</th>
<th>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb</th>
<th>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</th>
</tr>
</thead>
</table>

### Table 10

Model Component #8 - Bulbs in Parallel

Which Bulb Will be Brighter?

| 1) Won’t work because they must be hooked to battery separately. | 2) Both the same as each other and the same as the single bulb.* | 3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb | 4) Both the same because they get equal electricity. Both dimmer or different than single bulb. |
intuitive knowledge that is much less structured. The mental models that are determined can be characterized by a combination of one of the possible responses from each of the eight components listed above. This research will also demonstrate that the set of overall models the students used is relatively small, given the number of all possible combinations of responses from each of the eight model components.
CHAPTER III

METHOD

Introduction

This chapter describes the methodology used in this study. It will present a description of the subjects, the materials used and the instrument designed for use in this study, the procedure used for the administration of the survey, and the scoring system used to analyze and tabulate the students' responses to the survey.

Subjects

The subjects for this study were 99 students: 33 sixth graders, 33 seventh graders, and 33 eighth graders who volunteered to fill out the survey during their normal school day near the end of the school year. The seventh graders had recently completed (within the past month) a unit on electricity and electric circuits that was comprised of standard textbook instruction and some hands-on activities building simple circuits with batteries and bulbs. The sixth and eighth graders had received no instruction that school year. The students attended an average-sized (Class B) middle school in Allegan, Michigan and came from predominantly low to middle class backgrounds, 55 of the students were girls and 44 were boys. Students were not screened or selected by the teachers or the researcher. This was done to allow the sample to be as heterogeneous and representative
of the school population as possible.

Materials

The materials consisted of a 30-question survey (Appendix B) that was made up of (a) open-ended drawings, (b) multiple-choice questions, and (c) free response questions. The questions were based on the informal interview previously conducted (Appendix A) and on the tables of predicted responses for each of the mental model components in Tables 3-10. Each question on the survey was designed to correlate directly with one or more of the model components. All model components were represented on the survey by multiple questions to check students' answers for internal consistency. Appendix C shows how each of the predicted responses for each model component correlates with the questions on the survey in Appendix B. The choices presented to the students in the multiple-choice questions were representative of the predicted responses; but, all questions allowed for students to make up their own responses or choose more than one response while providing explanations.

A sample of a D-cell battery and a flashlight bulb in a bulb holder with two electrical contacts, as per Shipstone's (1985) advice, were also available for the students' visual inspection. This was included so they could see a three dimensional visual representation of what was depicted in the diagrams on the survey. Students did not interact with or manipulate any of the electrical components as part of the survey.
Procedure

Students were asked to fill out the surveys in their regular science classes by their regular science teacher. The teachers were instructed by the researcher how to administer the surveys. They distributed the surveys to all students who wanted to fill them out. They then instructed them to fill out the survey on their own and to answer every question on the survey even if they had to guess. Students were instructed that there was no penalty for wrong answers or guessing. Students were informed in advance that they would derive no external benefits, grades or otherwise, for doing the survey nor would they receive any negative repercussions for choosing not to fill out the survey.

The teachers then showed the class the actual D-cell and informed them that this is what the survey is referring to when the term battery is used in a question or as part of a drawing. The teachers then showed the students the flashlight bulb in its bulb holder and demonstrated how the bulb fits into the bulb holder. They then explained that this is what the survey is referring to when the term bulb is used in a question or when a bulb and a holder are shown in a diagram.

The teachers were instructed not to help any students with the survey or to give any hints. They were only allowed to encourage the students to do the best they can and to try to answer every question on the survey. Teachers read the instructions to the students and stressed that the students were not to go back and change any answers once they have finished a question and moved on to the next question. Teachers were allowed to read any question to a student that they could not read or understand.
The surveys were returned to the researcher by the teacher and surveys that were incomplete or not correctly filled out were removed. Then 33 surveys from each grade level were randomly selected from the total number of surveys so that each grade level would have equal representation in the scoring process.

**Scoring**

The surveys were scored by comparing students’ diagrams and answers to the tables of expected responses for each model component. A separate scoring sheet (Appendix C) was used for each survey to summarize and categorize students’ answers for each of the model components. Students who generated answers that were different from the predicted responses were noted on the individual scoring sheet and the unexpected response was described on the scoring sheet. Students who used more than one predicted response for a model component were also noted and their responses were indicated on the scoring sheet. Notations were also made on the individual scoring sheet as to which responses were: (a) logically inconsistent with or contradicted previous responses, (b) ambiguous as to their meaning and therefore a possible contradiction exists, or (c) unable to be determined.

In evaluating the students’ responses, it was necessary to distinguish or rate them based on their level of logical consistency. Therefore, a rating system for student responses was used similar to the rating system developed by Vosniadou & Brewer (1992, 1994). They created categories of acceptable and unacceptable deviations with
which to rate students’ responses. Responses that clearly contradicted previous responses were deemed unacceptable. Responses which may point to a possible contradiction depending on: (a) how a word was used by a student; (b) a diagram that was drawn in an unclear manner; or (c) the misreading of words such as not, all, or some were deemed acceptable.

As students’ responses were analyzed, they were rated and marked on the score sheets on one of three levels:

1. Those responses that showed no contradictions with other responses from the same or other model components on the survey.

2. Those responses that showed a possible or potential contradiction with other responses, to the same or other model components, that could be explained by a semantic or reading error or an unclear diagram. These were deemed acceptable deviations.

3. Those responses that were totally inconsistent and/or contradictory with other responses from the same or other model components on the survey. These were deemed unacceptable deviations.

Responses that were logically inconsistent were relatively easy to rate as such. Examples of these responses include:

1. Drawings that show arrows depicting round trip flow and subsequent drawings with arrows depicting flow from both ends of the battery.

2. Answers that describe electricity as being like water flowing through pipes and subsequent answers that describe electricity as moving particles that carry energy with
them.

3. Drawings that show arrows depicting flow from both ends of the battery and multiple subsequent answers that describe electricity as giving off some energy at the bulb with the rest flowing back to the battery.

Responses that were deemed to be an acceptable deviation were more problematic to rate. A more thorough analysis of the student’s drawings, free responses, and multiple-choice answers had to be undertaken to determine if there was a clear contradiction or just a potential one. Examples of these responses include:

1. A drawing with some arrows missing indicating flow but with no other indication that more than one type of flow pattern was evident in the student’s answers.

2. The selection of two choices, from the choices presented, that were identical except for the word ‘not’.

3. Describing the battery as an active source of electricity and then subsequently stating that the battery doesn’t push the electricity it ‘supplies it’.

**Grouping of Students**

Using the individual score sheets, along with the actual surveys, students were then sorted into four groups for further analysis as to the presence and description of mental models. These groups were determined based on the logical consistency of the students’ answers within and across model components. Since the logical consistency of the responses within and across model components was the main criteria for the
subsequent characterizing and assigning of mental models, it was necessary to be strict
in the grouping of students. Therefore, the following characteristics were developed for
each group:

**Group 1** - Students who used one predicted response per model component.
There were no acceptable deviations or logical inconsistencies within or across model
components.

**Group 2** – Students who used more than one predicted response or a response
that was not predicted for one or more model components. There were no acceptable
deviations or logical inconsistencies within or across model components.

**Group 3** – Students who used more than one predicted response or a response
that was not predicted for one or more model components. Responses produced only one
acceptable deviation within or across components.

**Group 4** – Students who used more than one predicted response or a response
that was not predicted for one or more model components. Responses produced more
than one acceptable deviation within or across components, at least one unacceptable
deviation, or more than one model component was undetermined.

Students belonging to Groups 1 and 2 were assigned and analyzed first because
they showed no contradictions within any of their responses. According to the
definitions and characteristics of mental models laid forth previously, these students
should have very clear mental models exhibited in their explanations to each model
component.
It became necessary to add Group 2 to the scoring system after the fact because the students in this group used responses that were not predicted or in ways that were not predicted but there were no logical inconsistencies found in their answers. This occurred for two reasons:

1. First, some of the students used responses that were not found in previous research or the pilot interviews. For example, saying that live energy flows out of the battery and dead energy flows back and that the filament burns the electrons up and that’s what makes the light.

2. Secondly, some of the students used more than one predicted response for a model component that did not cause a contradiction. For example, saying that both types (+&-) of electricity meet at the bulb and explode causing heat and light does not directly contradict the explanation that the wires in the bulb heat up and glow giving off light.

Students belonging to Group 3 were also incorporated into the data because previous research has shown that inconsistencies of indeterminate origin do not necessarily negate the presence or use of a mental model (Vosniadou & Brewer, 1992, 1994). They just make it more difficult to say with any certainty whether or not a mental model exists and what its structure might be. This is especially true if the error can be traced to a semantic error or if the student’s answer causing the apparent contradiction is ambiguous as to its meaning. The nature of the measuring instrument designed for this study does not allow for follow up clarification to ambiguous answers. However, in order to be strict and rigorous in analyzing the data and so as not to be accused of
manufacturing consistency in the interpretation of students' responses, it was decided to only allow one acceptable deviation for this group. This methodology is identical to both Vosniadou & Brewer's studies (1992, 1994) on which this study is based.

Students whose responses did not meet the stringent requirements of Groups 1, 2, and 3 were placed in Group 4 for later analysis. After a description of the actual mental models used was generated from the first three groups; this group was then analyzed for the possible presence of (a) the same models, (b) mixed models, or (c) even possible other models not found in the first three groups. This would keep the inconsistencies and inaccuracies of the responses in Group 4 from "muddying" the data from the groups whose answers were clear and internally consistent.

Construction of Mental Models

The demographics of each group and the frequency of each response used for each model component at each grade level were tabulated. The mental models used in each group were then constructed by linking together each student's responses from each of the eight model components. The descriptions of these models were generated by describing these links between model components. Students with the same or very similar links were assumed to have used the same mental model with slight variations noted in the model's description.

In constructing these models it was noted that Component 2 – Path of Flow (Table 4) was the most useful in determining which mental model a student was using.
Therefore, models were classified and named based on the four different types of flow that were used by the students. There were four basic model types with each one having a few variations:

**Type 1** - Round trip flow, leaving one end of the battery and returning to the other end, two wires needed.

**Type 2** - One way flow, leaving both ends of the battery and meeting at the bulb, 2 wires needed.

**Type 3** - One way flow, leaving one end of the battery, 1 or 2 wires needed.

**Type 4** - Round Trip flow, leaving one end of the battery and returning to the same end, one or two wires needed.

The basic model types were designated Type 1-4. The letters A, B, or C were used after the number to distinguish between variations of the same basic model type. So models designated 1A, 1B, and 1C would all be variations of Model 1, and models designated 2AB and 2AC would be variations of Model 2A.
CHAPTER IV

RESULTS

Introduction

This chapter will present the data collected for this study and its subsequent analysis. The results are presented by group based on the previous group descriptions.

A short description of each group is included again with the data. This chapter also includes a detailed description of the mental models determined by this study.

Distribution of Groups

The distribution of students into groups based on the internal logical consistency of their responses is shown on Table 11.

Table 11

Distribution of Groups By Grade Level

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Total Groups 1,2,3</th>
<th>Group 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th Graders</td>
<td>0</td>
<td>3</td>
<td>9</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td>7th Graders</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>8th Graders</td>
<td>10</td>
<td>4</td>
<td>6</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Totals</td>
<td>12</td>
<td>9</td>
<td>21</td>
<td>42</td>
<td>57</td>
</tr>
</tbody>
</table>

The groups with the highest level of logical consistency, Groups 1 & 2, had a
majority of eighth graders. This finding agrees with previous findings by Vosniadou & Brewer (1992, 1994) and Borges & Gilbert (1999) that older students tended to have more complex and logically consistent mental models than younger students. However, the trend did not progress consistently downward with age since it was the seventh graders who had the highest number of students that were logically inconsistent, as shown in Group 4. This finding is particularly interesting given the fact that, as a group, they had just completed a unit on electricity and electric circuits. This would seem to indicate that the effects of instruction made the students more logically inconsistent as they attempted to fit the knowledge pieces they had acquired into their existing knowledge structures. This trend was also reported by Vosniadou & Brewer’s 1994 study.

Another interesting observation can be made when comparing this data with Vosniadou & Brewer’s two previous studies (1992, 1994) on mental models. Vosniadou & Brewer’s 1992 study documented student’s mental models that contained one component and they found that 80% of the students met their criteria for logical consistency. In their 1994 study, where the mental models consisted of four components, they found that 68% of the students met their criteria for logical consistency within and across model components. In this study, where the mental models being measured and described consist of eight model components, 42% of the students met the same criteria for logical consistency within and across model components. Therefore, it appears that attempting to have students describe more complex models increases the likelihood of
their explanations becoming more logically inconsistent.

Group 1 Data Analysis

There were 12 students in this group: (a) ten eighth graders, (b) two seventh graders and (c) no sixth graders. These students used one predicted response per model component. The predicted responses for each model component were generated from previous research and the pilot interviews done prior to this research. These were described previously in Tables 3-10. The student's responses showed no acceptable deviations or logical inconsistencies within or across model components. An acceptable deviation, as explained in the previous chapter, is a possible contradiction or logical inconsistency that could be explained by a semantic error or a different reading interpretation of the question or by the student's answer being ambiguous as to its meaning. This group contains the students that were among the most logically consistent throughout the survey. They also used scientific explanations more often than unscientific explanations for most of the model components. The explanations that are considered to be the most scientific for a middle school student are designated with an asterisk (*) in the tables below. Tables 12-19 show the frequencies of each response for each model component at each grade level.

As a group, many of the students used scientific explanations to describe many of the model components. With 51 of the 120 explanations being considered scientific for a middle school student, this was the highest ratio of any of the four groups. They
Table 12

Frequencies of Group 1 Responses for Model Component #1

<table>
<thead>
<tr>
<th>Component #1 – Nature of Electricity</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity is a fluid (liquid or gas).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Electricity is pure energy, not a substance, like light or heat.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity is moving particles.</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4) Electricity is energy carried by moving particles.*</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 13

Frequencies of Group 1 Responses for Model Component #2

<table>
<thead>
<tr>
<th>Component #2 – Path of Flow</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Flow in one direction only from one end of the battery, a one-way trip.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other.</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>4) Round trip flow in one direction, both wires needed. Out one end and in the other. Electricity only makes the trip once.*</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

thought that (a) electricity is energy carried by moving particles, (b) electricity makes a round trip from one end of the battery back to the other end, and (c) as electricity flows some is used up by the device while the rest flows back to the battery.

Ten out of 12 described the battery as actively pushing the electricity out into the wires with six viewing it as being full of electricity while four viewed it as recharging
Table 14

Frequencies of Group 1 Responses for Model Component #3

<table>
<thead>
<tr>
<th>Component #3 – Mechanism of Action</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity flows from the battery to the device and is used up.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>4) Electricity flows to the device and gives off all its energy then flows back to the battery.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5) Electricity flows to the device and reacts, may be changed into something else.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6) No response</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 15

Frequencies of Group 1 Responses for Model Component #4

<table>
<thead>
<tr>
<th>Component #4 - Role of the Battery</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out.</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>3) Active - only pushes electricity around, pump-like, when it is unable to push the electricity it is dead.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge, it is dead.</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5) Active - produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 16
Frequencies of Group 1 Responses for Model Component #5

<table>
<thead>
<tr>
<th>Component #5 - Role of the Bulb</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity is released by the wires in the bulb causing light.</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2) Both types of electricity, (+ &amp; -), combine in bulb and react or explode causing light and heat.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 17
Frequencies of Group 1 Responses for Model Component #6

<table>
<thead>
<tr>
<th>Component #6 - Role of the Wires</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Lets electricity flow through like tubes.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2) Electricity flows on the outside of the wire, inside the insulation.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity flows through spaces in the wire.</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>4) Electricity flows from molecule to molecule in the wire.*</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>2) Wires already contain the stuff that flows.*</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3) Undetermined as to whether stuff that flows is there already or not.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1) It takes energy to get through the wire.*</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>2) It doesn't take energy to get through the wire.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3) Undetermined as to whether it takes energy to get through the wire.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 18
Frequencies of Group 1 Responses for Model Component #7

<table>
<thead>
<tr>
<th>Component #7 - Bulbs in Series</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won’t work because they must be hooked to battery separately.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 19
Frequencies of Group 1 Responses for Model Component #8

<table>
<thead>
<tr>
<th>Component #8 - Bulbs in Parallel</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won’t work because they must be hooked to battery separately.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.*</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>5) No Response</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

or producing the electricity. Nine out of 12 described the bulb as lighting up because the electricity gives off energy as it flows through the little wires causing them to heat up and glow and give off light.

Nine out of 12 described electricity as flowing through spaces in the wire or from
molecule to molecule in the wire, and that it took energy to get through the wire. Seven said that the wires are empty of whatever it is that flows until it comes from the battery. The latter view being unscientific, but all the previous descriptions being scientific viewpoints for middle school students. As a group they were split as to whether the bulbs in series would be the same as each other or not, and that the parallel bulbs would be the same but dimmer or different than a single bulb.

The mental models used by this group were determined by linking together each student’s responses for each of the eight model components. Students with the same or very similar links were assumed to have used the same mental models with slight variations noted in the model’s description. Models were named based on what type of flow they utilized and on which other models they were similar to as described in the previous chapter.

Descriptions and Distribution of Mental Models

The descriptions and distribution of the models used by this group are described below:

**Model 1** – There were three eighth graders and one seventh grader who used this model. This is a round trip flow model where electricity flows out one end of the battery and in the other end. Electricity is described as particulate in nature that may or may not carry energy. The electricity gives off some of its energy, or some is used up at the bulb, and then flows back to the battery where it is recharged, changed back or more is
produced, it then goes back out again. Electricity makes the bulb light up as it flows through the filament by giving off energy causing the filament in the bulb to heat up and glow giving off light. Electricity flows from molecule to molecule in the wire and possibly through spaces in the wire. Some variations of this described the flow through the wires like flowing through tubes. It takes energy to flow through the wires and there may already be some of the stuff that flows in the wires before it is hooked up. Two bulbs in series would be dimmer than one bulb but they may or may not be the same as each other. If they are different from each other then the one first in the flow will use more electricity and be brighter. Two bulbs in parallel may or may not be brighter than one bulb, bulbs probably the same as each other.

Model 1A – There were three eighth graders who used this model. This model is almost the same as Model 1. This is a round trip flow model where electricity flows out one end of the battery and in the other end. Electricity is described as particulate in nature that may or may not carry energy. The electricity may give off all of its energy at the bulb before going back to the battery. The battery is full of electricity and forces it out when it is connected. Electricity causes the bulb to light because electricity is released in the bulb as light. Electricity flows from molecule to molecule in the wire and possibly through spaces in the wire. Some variations of this described the flow through the wires like flowing through tubes. It takes energy to flow through the wires, but the stuff that flows may not be present in the wires. Two bulbs in series would be dimmer than one bulb but the bulbs may or may not be the same as each other. If they are
different from each other then the one first in the flow will use more electricity and be brighter. Two bulbs in parallel may or may not be brighter than one bulb, bulbs probably the same as each other.

**Model 1AB** – Two eighth graders used this model. This model was a blend of Model 1 and Model 1A. The description of the battery was like Model 1A, a device that is full of electricity and forces the electricity out. The description of how the bulb lights up was like Model 1, electricity makes the bulb light up as it flows through the filament by giving off energy causing the filament in the bulb to heat up and glow giving off light. Otherwise, it was similar to Model 1.

**Model 1B** – One eighth grader used this model. This was also very similar to Model 1 with these differences: (a) the battery is a passive storage tank of electricity, (b) the wires draw the electricity out, (c) the electricity only makes the round trip once, and (d) the wires are empty of the stuff that flows before being connected.

**Model 2** – One eighth grader used this model. Electricity makes a one-way trip from both ends of the battery and meets at the bulb. It is particulate in nature and may or may not carry energy with it. The battery is full of electricity and forces it out through the wires. The bulb lights because the electricity heats up the filament and makes it glow, giving off light. The electricity flows through the molecules or spaces in the wire and it takes energy to get through the wire. The wire is empty of the stuff that flows before being connected. Two bulbs in series or parallel are dimmer than a single bulb and one of the bulbs is brighter than the other because it gets more electricity.
Model 3 – One seventh grader used this model. Electricity makes a one-way trip from one end of the battery. It is particulate in nature and may or may not carry energy with it. The battery is a passive storage tank of electricity; the wires draw the electricity out. The electricity reaches the bulb and is completely used up. It makes the bulb light by making it heat up and glow. The electricity flows through the wires like tubes, which are empty of the stuff that flows until the battery is connected. Two bulbs in series or parallel are dimmer than a single bulb. When one bulb is closer to the battery or first in the flow, it will be brighter than the other because it gets more electricity.

Group 2 Data Analysis

There were nine students in this group: (a) four eighth graders, (b) two seventh graders, and (c) three sixth graders. These students used more than one predicted response or a response not predicted for one or more model components. The predicted responses for each model component were generated from previous research and the pilot interviews done prior to this research. These were previously described in Tables 3-10.

This group contains students that were among the most logically consistent throughout the survey. This group had a lower ratio of scientific explanations than Group 1, 24 out of 90, but it also produced some of the most interesting responses. There were some responses from this group that were not predicted, such as saying that the electricity turns from negative into positive at the bulb and then the battery turns it back to negative again. Also, they sometimes used combinations of predicted responses in
unexpected ways, such as saying that the battery was full of electricity and that it recharged the electricity when it returned. However, their responses still showed no logical inconsistencies or acceptable deviations. An acceptable deviation, as explained in the previous chapter, is a possible contradiction or logical inconsistency that could be explained by a semantic error or a different reading interpretation of the question or by the student’s answer being ambiguous as to its meaning. The explanations that are considered to be the most scientific for a middle school student are designated with an asterisk (*) in the tables below. Tables 20-27 show the frequencies of each response for each model component at each grade level.

Table 20

Frequencies of Group 2 Responses for Model Component #1

<table>
<thead>
<tr>
<th>Component #1 – Nature of Electricity</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is Electricity?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity is a fluid (liquid or gas).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Electricity is pure energy, not a substance, like light or heat.</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3) Electricity is moving particles.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Electricity is energy carried by moving particles.*</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

As mentioned above, the students in this group used many scientific responses but they also used some responses that weren’t predicted, as well as combinations of predicted responses that weren’t expected. The responses that weren’t predicted were:

1. “Live energy flows out of the battery and dead energy flows back.”
2. “The filament burns the electrons up and that’s what makes the light.”
### Table 21

Frequencies of Group 2 Responses for Model Component #2

<table>
<thead>
<tr>
<th>Component #2 - Path of Flow</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity flow?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Flow in one direction only from one end of the battery, a one-way trip.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other.</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4) Round trip flow in one direction, both wires needed. Out one end and in the other end. Electricity only makes the trip once.*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 22

Frequencies of Group 2 Responses for Model Component #3

<table>
<thead>
<tr>
<th>Component #3 – Mechanism of Action</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity work?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity flows from the battery to the device and is used up.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4) Electricity flows to the device and gives off all its energy then flows back to the battery.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5) Electricity flows to the device and reacts, may be changed into something else.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6) Response different than predicted responses.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7) More than one predicted response used.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 23
Frequencies of Group 2 Responses for Model Component #4

<table>
<thead>
<tr>
<th>Component #4 - Role of the Battery</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does a battery work?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out.</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3) Active – only pushes electricity around, pump-like, when it is unable to push the electricity it is dead.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge, it is dead.</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5) Active – produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6) More than one predicted response used</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>7) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 24
Frequencies of Group 2 Responses for Model Component #5

<table>
<thead>
<tr>
<th>Component #5 - Role of the Bulb</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does a bulb work?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity is released by the wires in the bulb causing light.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2) Both types of electricity, (+ &amp; -), combine in bulb and react or explode causing light and heat.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.*</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 25
Frequencies of Group 2 Responses for Model Component #6

<table>
<thead>
<tr>
<th><strong>Component #6 - Role of the Wires</strong></th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity get through the wires?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Lets electricity flow through like tubes.</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2) Electricity flows on the outside of the wire, inside the insulation.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Electricity flows through spaces in the wire.</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>4) Electricity flows from molecule to molecule in the wire.*</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5) More than one predicted response used.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2) Wires already contain the stuff that flows.*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Undetermined as to whether stuff that flows is there already or not.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1) It takes energy to get through the wire.*</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>2) It doesn’t take energy to get through the wire.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) Undetermined as to whether it takes energy to get through the wire.</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 26
Frequencies of Group 2 Responses for Model Component #7

<table>
<thead>
<tr>
<th><strong>Component #7 - Bulbs in Series</strong></th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which bulb will be brighter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Won’t work because they must be hooked to battery separately.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 27

Frequencies of Group 2 Responses for Model Component #8

<table>
<thead>
<tr>
<th>Component #8 - Bulbs in Parallel</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which bulb will be brighter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Won't work because they must be hooked to battery separately.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6) No Response</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

3. "Two bulbs in parallel will be the same brightness as each other and brighter than a single bulb."

4. "Two bulbs in series will have different brightness. One will be dimmer than a single bulb and one will be the same as a single bulb."

Because there were no internal inconsistencies, these responses still fit into a description of the mental models used by the students. The mental models used by this group were determined the same way as the previous group. Three of the models used were the same as the previous group’s and three of them were variations on models from the previous group’s.

Descriptions and Distribution of Mental Models

The descriptions and distribution of the models used by this group are described
Model 1 – Two eighth graders used this model as described above.

Model 1AB – One sixth grader used this model as described above.

Model 1C – One eighth grader used this model. It is very similar to Model 1 as described above. Electricity is pure energy, not a substance, can’t be seen or hard to see, travels very fast. The electrons flow to the device where they are burned up giving off some of their energy or just give off energy as light, then flow back to the battery to be recharged, and flow back out again. The bulb lights because the filament burns the electrons or releases energy from the electrons. Electricity travels through the wires just like travelling through tubes or through the spaces in the wire. In series or parallel, both bulbs are probably dimmer than a single bulb and probably the same as each other.

Model 2A – One sixth, one seventh, and one eighth grader used this model. It is similar to Model 2 described above with these differences: (a) electricity is composed of positive and negative energy or particles that meet at the bulb and combine or react to form light and may also heat up the filament, (b) electricity flows through the wire just like flowing through tubes or through the spaces in the wires, and (c) two bulbs in parallel or series are both dimmer than a single bulb and are both the same brightness.

Model 3 – One seventh grader used this model as described above.

Model 3A – One sixth grader used this model. It is similar to Model 3 described above with these differences: (a) the battery is not a passive storage tank but is actively producing electricity and pushing it out through the wires, (b) electricity is released by
the bulb filament making it light up, (c) electricity flows from molecule to molecule, and (d) two bulbs in series or parallel will be different from each other and could possibly be brighter than a single bulb.

Group 3 Data Analysis

There were 21 students in this group: (a) six eighth graders, (b) six seventh graders, and (c) nine sixth graders. These students used more than one predicted response or a response not predicted for one or more model components, as described above. The predicted responses for each model component were generated from previous research and the pilot interviews done prior to this research. These were previously described in Tables 3-10.

The student's responses showed only one acceptable deviation within or across components but no logical inconsistencies. An acceptable deviation, as explained in the previous chapter, is a possible contradiction or logical inconsistency that could be explained by a semantic error or a different reading interpretation of the question or by the student's answer being ambiguous as to its meaning. This group had a low ratio of scientific to unscientific responses, 63 out of 210; and, like Group 2, produced a number of responses that were not predicted, which are described below. This group also had a number of instances where combinations of expected responses were used in unexpected ways such as: (a) the battery produces and recharges the electricity, (b) electricity flows through the spaces in the wire and on the outside of the wire, and (c) electricity is moving
Table 28
Frequencies of Group 3 Responses for Model Component #1

<table>
<thead>
<tr>
<th>Component #1 – Nature of Electricity</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is Electricity?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity is a fluid (liquid or gas).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Electricity is pure energy, not a substance, like light or heat.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3) Electricity is moving particles.</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4) Electricity is energy carried by moving particles.*</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>5) More than one predicted response used.</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 29
Frequencies of Group 3 Responses for Model Component #2

<table>
<thead>
<tr>
<th>Component #2 - Path of Flow</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity flow?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Flow in one direction only from one end of the battery, a one-way trip.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires.</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other.</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>4) Round trip flow in one direction, both wires needed. Out one end and in the other. Electricity only makes the trip once.*</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

particles and it is energy carried by moving particles. The explanations that are considered to be the most scientific for a middle school student are designated with an asterisk (*) in the tables below. Tables 28-35 show the frequencies of each response for
Table 30

Frequencies of Group 3 Responses for Model Component #3

<table>
<thead>
<tr>
<th>Component #3 – Mechanism of Action</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity flows from the battery to the device and is used up.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up.</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>4) Electricity flows to the device and gives off all its energy then flows back to the battery.</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>5) Electricity flows to the device and reacts, may be changed into something else.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 31

Frequencies of Group 3 Responses for Model Component #4

<table>
<thead>
<tr>
<th>Component #4 - Role of the Battery</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank.</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out.</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3) Active - only pushes electricity around, pump-like, when it is unable to push the electricity it is dead.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge, it is dead.</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>5) Active - produces electricity inside it, when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>6) More than one predicted response used</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>
### Table 32

Frequencies of Group 3 Responses for Model Component #5

<table>
<thead>
<tr>
<th>Component #5 - Role of the Bulb</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does a bulb work?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity is released by the wires in the bulb causing light.</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2) Both types of electricity, (+ &amp; -), combine in bulb and react or explode causing light and heat.</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.*</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 33

Frequencies of Group 3 Responses for Model Component #6

<table>
<thead>
<tr>
<th>Component #6 - Role of the Wires</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity get through the wires?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Lets electricity flow through like tubes.</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>2) Electricity flows on the outside of the wire, inside the insulation.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3) Electricity flows through spaces in the wire.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4) Electricity flows from molecule to molecule in the wire.*</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>2) Wires already contain the stuff that flows.*</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3) Undetermined as to whether stuff that flows is there already or not.</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>1) It takes energy to get through the wire.*</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>2) It doesn’t take energy to get through the wire.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3) Undetermined as to whether it takes energy to get through the wire.</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 34

Frequencies of Group 3 Responses for Model Component #7

<table>
<thead>
<tr>
<th>Component #7 - Bulbs in Series</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which bulb will be brighter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Won’t work because they must be hooked to battery separately.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 35

Frequencies of Group 3 Responses for Model Component #8

<table>
<thead>
<tr>
<th>Component #8 - Bulbs in Parallel</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Which bulb will be brighter?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Won’t work because they must be hooked to battery separately.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.*</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

each model component at each grade level.

The responses used by this group that weren’t predicted were:

1. Drawings that indicated electricity flowing to and from the same end of the battery.
2. “Electricity bounces back and forth inside the bulb filament and makes it light up.”

3. The battery doesn’t push the electricity through the wires it pulls it.

4. Electricity flows through wires because, “it is conducted by metal.”

5. Electricity flows through wires because, “it flows through wires.”

6. Electricity flows through wires because, “the molecules flow through the wire.”

7. “Two bulbs will give off more light than one”

8. Drawings indicated another battery needs to be added for parallel and series circuits to work.

9. In series circuit, “one bulb will be the same brightness as a single bulb but the other won’t be.”

Some of these statements still fit into existing models that were found in the first two groups. Five of the models used by this group were the same as models used by the first two groups. Four of the models used were variations of models used by the first two groups. However, this group also used a whole new type of model that was not predicted because it was not seen anywhere in the review of previous research nor did it surface in the pilot interviews. This model was a round-trip model but it indicated round-trip flow to and from one end of the battery. Students indicated this on their drawings, but this caused an acceptable deviation on one of the multiple-choice questions since it was not provided as one of the choices. There were other students in Group 4 who used this
model but had more than one acceptable deviation in their responses, this being one of them. Therefore, had this type of flow been included in as one of the choices in the multiple choice questions; there would have been more students with this model type in this group because they would have had only one acceptable deviation and not two.

Descriptions and Distribution of Mental Models

The descriptions and distribution of the models used by this group are described below:

Model 1 - One sixth, one seventh, and one eighth grader used this model as described above.

Model 1A - One eighth grader used this model as described above.

Model 1AB - One sixth and one eighth grader used this model as described above.

Model 1C - One sixth and one eighth grader used this model as described above.

Model 2A - One sixth grader used this model as described above.

Model 2AB - Two sixth, one seventh, and two eighth graders used this model. This model is the same as Model 2A with these differences: (a) the battery makes or charges the electricity and (b) it flows through the wires like tubes or because wires conduct electricity.

Model 2AC - Two sixth graders used this model. This model is also the same as Model 2A with these differences: (a) the battery is a passive storage tank of electricity,
(b) the wires draw the electricity out, and (c) it may or may not take energy for the 
electricity to flow through the wires.

**Model 3A** – One seventh grader used this model as described above.

**Model 3B** – One seventh grader used this model. Electricity makes a one-way 
trip from one end of the battery. It is pure energy, not a substance. When it reaches the 
bulb it reacts, heats the filament until it glows and gives off light. The battery is full of 
electricity and pushes it out into the wires. It flows through the spaces in the wires, 
which may contain some of the stuff that flows already but it takes energy for the 
electricity to flow. Two bulbs in parallel or series are both dimmer than a single bulb and 
may or may not both be the same brightness.

**Model 4** - One seventh grader used this model. Electricity makes a round trip to 
and from the same end of the battery. It is particulate in nature and may or may not carry 
energy with it. Electricity is composed of positive and negative energy or particles that 
combine at the bulb and possibly react to form light. The battery is a passive storage tank 
of electricity, the wires draw the electricity out. The electricity flows through the wires 
like tubes, which are empty of the stuff that flows until the battery is connected. Bulbs 
in series or parallel will be dimmer than a single bulb and will probably be the same as 
each other.

**Model 4A** - One sixth grader used this model. It is similar to Model 4 with these 
differences: (a) electricity flows to the bulb and releases some or all of its energy as light 
and goes back to the battery, (b) the battery is full of electricity and pushes it out into the
wires, and (c) bulbs in series or parallel will be the same as each other and the same as a single bulb.

**Model 4B** – One seventh grader used this model. It is similar to Model 4 with these differences: (a) electricity flows to the bulb and is used up, (b) it is released in the bulb as light, (c) the battery is a passive storage tank of electricity, (d) the wires draw the electricity out, and (e) bulbs in series or parallel will be the same as each other and may or may not be the same as a single bulb.

**Summary of Data Analysis for Groups 1, 2 & 3**

The data from Groups 1, 2 & 3 were combined to generate a more complete picture of the results. These three groups were chosen because they represent all the subjects whose responses did not show any obvious logical inconsistencies. Since this is the main criterion for evidence of a mental model, it would imply that the data from these three groups should contain descriptions of all the mental models the students used. There were 42 subjects in Groups 1, 2, & 3 combined; (a) 20 eighth graders, (b) 10 seventh graders and (c) 12 sixth graders. Tables 36–43 show the frequencies of each response for each model component at each grade level for all three groups. Again, the explanations that are considered to be the most scientific for a middle school student are designated with an asterisk (*) in the tables below.
### Table 36
Frequencies of Group 1,2&3 Responses for Model Component #1

<table>
<thead>
<tr>
<th>Component #1 – Nature of Electricity</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity is a fluid (liquid or gas).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Electricity is pure energy, not a substance, like light or heat.</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3) Electricity is moving particles.</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4) Electricity is energy carried by moving particles.*</td>
<td>8</td>
<td>7</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>5) More than one predicted response used.</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 37
Frequencies of Group 1,2&3 Responses for Model Component #2

<table>
<thead>
<tr>
<th>Component #2 - Path of Flow</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Flow in one direction only from one end of the battery, a one-way trip.</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires.</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other.</td>
<td>4</td>
<td>2</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>4) Round trip flow in one direction, both wires needed. Out one end and in the other end. Electricity only makes the trip once.*</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
### Table 38
Frequencies of Group 1,2&3 Responses for Model Component #3

<table>
<thead>
<tr>
<th>Component #3 – Mechanism of Action</th>
<th>6&lt;sup&gt;th&lt;/sup&gt;</th>
<th>7&lt;sup&gt;th&lt;/sup&gt;</th>
<th>8&lt;sup&gt;th&lt;/sup&gt;</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity flows from the battery to the device and is used up.</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up.</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
<td>2</td>
<td>3</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>4) Electricity flows to the device and gives off all its energy then flows back to the battery.</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>5) Electricity flows to the device and reacts, may be changed into something else.</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6) Response different than predicted responses.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7) More than one predicted response used.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>8) No response</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Summary and Distribution of Mental Models

By combining the descriptions of the models used from each group, one can get a more complete picture of all the models determined by this study. Table 44 shows a comparison of all the models and their model components. Beneath each model name is a set of numbers in parentheses which represents the frequency of each model for each grade. The first number is the frequency for Grade 6, the second for Grade 7, and the third for Grade 8. The last number gives the total for all grades. The structure of the table is such that the models are grouped by type and are arranged in a loosely determined order from most scientific to least scientific. This is a general order and not
### Table 39
Frequencies of Group 1,2&3 Responses for Model Component #4

**Component #4 - Role of the Battery**

<table>
<thead>
<tr>
<th>How does a battery work?</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank.</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out.</td>
<td>2</td>
<td>3</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>3) Active - only pushes electricity around, pump-like, when it is unable to push the electricity, it is dead.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge, it is dead.</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>5) Active - produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>6) More than one predicted response used</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>7) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 40
Frequencies of Group 1,2&3 Responses for Model Component #5

**Component #5 - Role of the Bulb**

<table>
<thead>
<tr>
<th>How does a bulb work?</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity is released by the wires in the bulb causing light.</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>2) Both types of electricity, (+ &amp; -), combine in bulb and react or explode causing light and heat.</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.*</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 41

Frequencies of Group 1,2&3 Responses for Model Component #6

<table>
<thead>
<tr>
<th>Component #6 - Role of the Wires</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Lets electricity flow through like tubes.</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>2) Electricity flows on the outside of the wire, inside the insulation.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3) Electricity flows through spaces in the wire.</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>4) Electricity flows from molecule to molecule in the wire.*</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>10</td>
<td>8</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>2) Wires already contain the stuff that flows.*</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>3) Undetermined as to whether stuff that flows is there already or not.</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>1) It takes energy to get through the wire.*</td>
<td>7</td>
<td>6</td>
<td>16</td>
<td>29</td>
</tr>
<tr>
<td>2) It doesn't take energy to get through the wire.</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3) Undetermined as to whether it takes energy to get through the wire.</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

meant to be exact. A model to the immediate left or right of another is not necessarily more or less scientific. But as one moves across the table of mental models, from models designated Type 1 to the models designated Type 4, one encounters models that are increasingly more unscientific.

For the purposes of this study, the most scientific model possible would be a model composed of all the explanations with an asterisk (*) listed in the tables above. These explanations are summarized below in Table 45. This table represents the most
Table 42
Frequencies of Group 1,2&3 Responses for Model Component #7

<table>
<thead>
<tr>
<th>Component #7 – Bulbs in Series</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won't work because they must be hooked to battery separately.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
<td>4</td>
<td>6</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 43
Frequencies of Group 1,2&3 Responses for Model Component #8

<table>
<thead>
<tr>
<th>Component #8 – Bulbs in Parallel</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won't work because they must be hooked to battery separately.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.*</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.</td>
<td>7</td>
<td>6</td>
<td>11</td>
<td>24</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6) No Response</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

scientific model expected in this study. Students’ models can be described as being more or less scientific by comparing them to this model.
<table>
<thead>
<tr>
<th>Model Components</th>
<th>Model 1 ((1,2,7=10))</th>
<th>Model 1A ((0,0,3=3))</th>
<th>Model 1AB ((2,0,3=5))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>Particulate, may or may not carry energy.</td>
<td>Same as Model 1</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>Round Trip – Leaves one end of the battery, returns to the other. Probably repeats the trip.</td>
<td>Same as Model 1</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Electricity gives off some of its energy or some is used up at the bulb, then flows back to the battery</td>
<td>Electricity may give off all its energy at the bulb before going back to the battery</td>
<td>Electricity gives off some or all of its energy or some is used up at the bulb, then flows back to the battery</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Battery recharges, changes back or produces more electricity</td>
<td>Battery is full of electricity and forces it out into the wires</td>
<td>Same as Model 1A</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>Bulb lights when electricity makes filament heat up and glow.</td>
<td>Bulb lights because electricity is released in the bulb as light</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Electricity flows from molecule to molecule or through spaces in the wire (might flow like through tubes). It takes energy to flow through the wires, the stuff that flows may already be there</td>
<td>Same as Model 1</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Bulbs will be dimmer than single bulb, may or may not be the same as each other. If not, the one first in flow will be brighter</td>
<td>Same as Model 1</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Bulbs may or may not be brighter than single bulb, probably the same as each other.</td>
<td>Same as Model 1</td>
<td>Same as Model 1</td>
</tr>
<tr>
<td>Model Components</td>
<td>Model 1B ((0,0,1=1))</td>
<td>Model 1C ((1,0,2=3))</td>
<td>Model 2 ((0,0,1=1))</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>1) Nature of Electricity</td>
<td>Same as Model 1</td>
<td>Electricity is pure energy not a substance, hard to see, travels very fast</td>
<td>Particulate, may or may not carry energy</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>Same as Model 1, but makes trip only once.</td>
<td>Same as Model 1</td>
<td>One way Trip - Flows from both ends of the battery</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Same as Model 1</td>
<td>Electrons are burned or give off some of their energy or some is used up at the bulb, then flows back to the battery</td>
<td>Electricity meets at the bulb and gives off energy</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Battery is a passive storage tank, wires draw electricity out</td>
<td>Same as Model 1</td>
<td>Battery is full of electricity and forces it out into the wires</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>Same as Model 1</td>
<td>Bulb lights because filament burns the electrons or releases energy from the electrons</td>
<td>Bulb lights when electricity makes filament heat up and glow.</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Same as Model 1, but wires are empty of stuff that flows</td>
<td>Same as Model 1, but wires are empty of stuff that flows</td>
<td>Electricity flows through the molecules or spaces in the wire. It takes energy to get through the wire, wire is empty of stuff that flows</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Same as Model 1</td>
<td>Bulbs probably dimmer than single bulb and probably the same as each other</td>
<td>Bulbs are dimmer than single bulb and one is brighter because it gets more electricity</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Same as Model 1</td>
<td>Bulbs probably dimmer than single bulb and probably the same as each other</td>
<td>Bulbs are dimmer than single bulb and one is brighter because it gets more electricity</td>
</tr>
</tbody>
</table>
| Model Components | Model 2A  
(2,1,1=4) | Model 2AB  
(2,1,2=5) | Model 2AC  
(2,0,0=2) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>Composed of positive and negative energy or particles</td>
<td>Same as Model 2A</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>Same as Model 2</td>
<td>Same as Model 2</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Positive and negative electricity meet at the bulb and combine.</td>
<td>Same as Model 2A</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Same as Model 2</td>
<td>Battery makes or charges up the electricity then sends it out.</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>When positive and negative electricity meet at the bulb they combine or react and cause light, may also heat up filament.</td>
<td>Same as Model 2A</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Electricity flows through wires like flowing through tubes or through spaces in the wires. It takes energy to get through the wire, wire is empty of stuff that flows</td>
<td>Electricity flows through wires like tubes or just flows because wire conducts. Wire may be empty of stuff that flows, probably takes energy for it to flow.</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Bulbs are dimmer than single bulb and may both be the same brightness</td>
<td>?</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Bulbs are dimmer than single bulb and may both be the same brightness</td>
<td>?</td>
</tr>
</tbody>
</table>
Table 44--continued

<table>
<thead>
<tr>
<th>Model Components</th>
<th>Model 3 (0,2,0=2)</th>
<th>Model 3A (1,1,0=2)</th>
<th>Model 3B (0,1,0=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>Particulate, may or may not carry energy</td>
<td>Same as Model 3</td>
<td>Electricity is pure energy</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>One way Trip – Flows from one end of battery</td>
<td>Same as Model 3</td>
<td>Same as Model 3</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Electricity flows from battery to bulb and is used up</td>
<td>Same as Model 3</td>
<td>Electricity reaches bulb and reacts to make the bulb light</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Battery is a passive storage tank, wires draw electricity out</td>
<td>Battery produces electricity and pushes it out into the wires</td>
<td>Battery is full of electricity and forces it out into the wires</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>Bulb lights when electricity makes filament heat up and glow.</td>
<td>Electricity is released by the bulb making it light up</td>
<td>When electricity reacts, it heats up the filament, makes it glow and give off light</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Electricity flows through wires like tubes. Wires are empty of stuff that flows.</td>
<td>Electricity flows from molecule to molecule. Wires are empty of stuff that flows</td>
<td>Electricity flows through spaces in the wires. They may contain stuff that flows already but it takes energy for it to flow</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Bulbs are dimmer than single bulb, first bulb in flow will be brighter</td>
<td>Bulbs are different from each other and could possibly be brighter than a single bulb</td>
<td>Bulbs are dimmer than single bulb, may or may not be the same brightness</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Bulbs are dimmer than single bulb, first bulb in flow will be brighter</td>
<td>Bulbs are different from each other and could possibly be brighter than a single bulb</td>
<td>Bulbs are dimmer than single bulb, may or may not be the same brightness</td>
</tr>
</tbody>
</table>
Table 44--continued

<table>
<thead>
<tr>
<th>Model Components</th>
<th>Model 4 (0,1,0=1)</th>
<th>Model 4A (1,0,0=1)</th>
<th>Model 4B (0,1,0=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>Composed of positive and negative energy or particles</td>
<td>Particulate, may or may not carry energy</td>
<td>Same as Model 4A</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>Round Trip – Leaves and returns to the same end of the battery</td>
<td>Same as Model 4</td>
<td>Same as Model 4</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Positive and negative electricity meet at the bulb and combine.</td>
<td>Electricity gives off some or all of its energy then flows back to the battery</td>
<td>Same as Model 4A</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Battery is a passive storage tank, wires draw electricity out</td>
<td>Battery is full of electricity and forces it out into the wires</td>
<td>Same as Model 4</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>When positive and negative electricity meet at the bulb they combine or react and cause light.</td>
<td>Electricity is released by the bulb making it light up</td>
<td>Same as Model 4A</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Electricity flows through wires like tubes. Wires are empty of stuff that flows.</td>
<td>Same as Model 4</td>
<td>Same as Model 4</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Bulbs are dimmer than single bulb and will probably be the same as each other</td>
<td>Bulbs will be the same as each other and the same as a single bulb</td>
<td>Bulbs will be the same as each other and may or may not be the same as a single bulb</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Bulbs are dimmer than single bulb and will probably be the same as each other</td>
<td>Bulbs will be the same as each other and the same as a single bulb</td>
<td>Bulbs will be the same as each other and may or may not be the same as a single bulb</td>
</tr>
</tbody>
</table>
Table 45
The Components of a Scientific Model

<table>
<thead>
<tr>
<th>Model Components</th>
<th>Scientific Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Nature of Electricity</td>
<td>Electricity is energy carried by moving particles.*</td>
</tr>
<tr>
<td>2) Path of Flow</td>
<td>Round trip flow in one direction, both wires needed. Out one end and in the other end. Electricity only makes the trip once.*</td>
</tr>
<tr>
<td>3) Mechanism of Action</td>
<td>Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
</tr>
<tr>
<td>4) Role of the Battery</td>
<td>Active - produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
</tr>
<tr>
<td>5) Role of the Bulb</td>
<td>Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.*</td>
</tr>
<tr>
<td>6) Role of the Wires</td>
<td>Electricity flows from molecule to molecule in the wire.*</td>
</tr>
<tr>
<td>7) Bulbs in Series</td>
<td>Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
</tr>
<tr>
<td>8) Bulbs in Parallel</td>
<td>Both the same as each other and the same as the single bulb.*</td>
</tr>
</tbody>
</table>

Table 46 shows a summary of the distribution of mental models across grade levels. An analysis of the distribution of these models across grade levels reveals that: (a) most of the eighth graders, 16 out of 20, used mental models that were at the more scientific end of the table, Type 1; (b) most of the seventh graders, 6 out of 10, were at the less scientific end of the table, Types 3 & 4, and (c) the sixth graders were fairly spread out with a large number, 6 out of 12, in the middle of the table. This shows that not only were the eighth graders more logically consistent, as shown in Table 11, but they were also more scientific in their responses. In other words, not only could they give more
Table 46

A Summary of the Distribution of Mental Models Across Grade Levels

<table>
<thead>
<tr>
<th>Model Numbers</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>1A</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1AB</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>1B</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1C</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2A</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2AB</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>2AC</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3A</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3B</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4A</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4B</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

scientifically correct responses but they also were able to use those responses in a logically consistent manner. This data, and the fact that the eighth graders received no formal instruction on electricity during the previous school year, would indicate that these knowledge pieces are firmly connected in a well-established knowledge structure by this point in their education. This may or may not be a positive finding, depending on whether or not a particular student has a scientific or unscientific structure of these concepts.

The seventh grade data on the other hand shows that only a month or less after instruction, many students used unscientific mental models as well as having a higher
level of logical inconsistency, also shown in Table 11. The sixth graders used mental
models that were spread fairly evenly across the spectrum. They had received no
instruction during the previous school year and were the youngest group. The finding
that models that are more scientific were used by older students and models that are less
scientific were used by younger students is consistent with previous research (Borges &

Group 4 Data Analysis

There were 57 subjects in this group: (a) 13 eighth graders, (b) 23 seventh graders
and (c) 21 sixth graders. These subjects used more than one predicted response or a
response not predicted for one or more model components. The predicted responses for
each model component were generated from previous research and the pilot interviews
done prior to this research. These were previously described in Tables 3-10. The
subject’s responses showed one or more of the following: (a) more than one acceptable
deviations within or across model components, (b) at least one obvious logical
inconsistency within or across model components, or (c) more than one model
component was undetermined.

An acceptable deviation, as explained in the previous chapter, is a possible
contradiction or logical inconsistency that could be explained by a semantic error or a
different reading interpretation of the question or by the subject’s answer being
ambiguous as to its meaning.
This group, by definition, was the most logically inconsistent of all the students. This made it impossible to determine the specific mental models used by these students given the definitions of a mental model on which this study is based. This doesn’t mean that these students didn’t use any mental models; they just could not be described in detail using the rigorous criteria for mental models set up by this study. However, the responses given by this group were tabulated as before and appear in Tables 47-54. Again, the explanations that are considered to be the most scientific for a middle school student are designated with an asterisk (*) in the tables below.

Table 47

Frequencies of Group 4 Responses for Model Component #1

<table>
<thead>
<tr>
<th>Component #1 – Nature of Electricity</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is Electricity?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Electricity is a fluid (liquid or gas).</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) Electricity is pure energy, not a substance, like light or heat.</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>3) Electricity is moving particles.</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4) Electricity is energy carried by moving particles.*</td>
<td>12</td>
<td>16</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>7) No response</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

This group had the highest ratio of unscientific responses, 435 out of 570. They frequently used combinations of expected responses in unexpected ways, 108 responses out of 570. They also produced the highest number of unpredicted responses, 36. This produced many logical inconsistencies. Some of the responses given that were not
Table 48

Frequencies of Group 4 Responses for Model Component #2

<table>
<thead>
<tr>
<th>Component #2 - Path of Flow</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>How does electricity flow?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Flow in one direction only from one end of the battery, a one-way trip.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires.</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other.</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>4) Round trip flow in one direction, both wires needed. Out one end and in the other end. Electricity only makes the trip once.*</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>16</td>
<td>16</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>7) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

predicted and not previously mentioned in the other groups were:

1. “...positive particles (protons) flow from the battery to the bulb and negative particles (electrons) flow back from the bulb to the battery.”

2. “...the molecules push each other out of the battery.”

3. “Electricity flows through the whole wire inside the plastic.”

4. “Electricity is atoms of energy.”

5. “Electricity flows only from the bulbs to the battery,” and “...the bulbs give off electricity.”

6. “Electricity carries sparks of light to the bulb.”
Table 49
Frequencies of Group 4 Responses for Model Component #3

<table>
<thead>
<tr>
<th>Component #3 – Mechanism of Action</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity flows from the battery to the device and is used up.</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up.</td>
<td>11</td>
<td>10</td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery.*</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>4) Electricity flows to the device and gives off all its energy then flows back to the battery.</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5) Electricity flows to the device and reacts, may be changed into something else.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>6) Response different than predicted responses.</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>7) More than one predicted response used.</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>8) No response</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Analysis and Distribution of Possible Models

As mentioned before, the responses given by this group were too logically inconsistent to use to describe any detailed, complete mental models as defined by this study. However, there were students within this group that consistently used a model type (1-4) throughout the survey. The model types were based on component #2 as previously discussed. While it is not possible to accurately place them on the Table of Mental Models (Table 44), it is possible to determine if they used a Type 1, 2, 3, or 4 model consistently. An tabulation of this kind is shown on Table 55. The table shows the frequencies for each model type used by grade level. Students who used more than
Table 50

Frequencies of Group 4 Responses for Model Component #4

<table>
<thead>
<tr>
<th>Component #4 – Role of the Battery</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank.</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out.</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>3) Active - only pushes electricity around, pump-like, when it is unable to push the electricity, it is dead.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge, it is dead.</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>5) Active – produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out.*</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>6) Response different than predicted responses.</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>7) More than one predicted response used</td>
<td>9</td>
<td>8</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>8) No response</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

one model type on the survey were placed in the Mixed Model type category and students whose model type could not be determined were placed in the Undetermined category.

This tabulation is not meant to imply that these Group 4 students were using a mental model to the extent that the other groups of students were. But there was enough consistency in their survey answers to infer that some form of knowledge structure was being used by at least 33 of the students in Group 4. As mentioned at the beginning of this chapter and in the review of previous research in Chapter II (Vosniadou & Brewer,
Table 51

Frequencies of Group 4 Responses for Model Component #5

<table>
<thead>
<tr>
<th>Component #5 – Role of the Bulb</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Electricity is released by the wires in the bulb causing light.</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>2) Both types of electricity, (+ &amp; -), combine in bulb and react or explode causing light and heat.</td>
<td>9</td>
<td>5</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products).</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light.*</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>5</td>
<td>9</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>7) No response</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

1994), it appears that if the complexity of the model to be described is reduced then the number of students who appear to be using that model increases. Such is the case here.

By using a simpler model description that is limited to: (a) type of flow, round trip or one way; (b) number of wires needed to the battery, one or two; and (c) connections with the battery, one or both ends, one can increase the apparent number of models found within the students’ explanations. The purpose of performing this analysis is to show that all the of students in Group 4 were not being totally inconsistent. They just did not meet the level of logical consistency set up by this study.

Based on this data one can see that the most used model type is Type 1, which was the most scientific model type. It was also the model type used most often by the eighth graders, while the sixth and seventh graders used Type 1 and Type 3 at about the
Table 52

Frequencies of Group 4 Responses for Model Component #6

<table>
<thead>
<tr>
<th>Component #6 – Role of the Wires</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Lets electricity flow through like tubes.</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>2) Electricity flows on the outside of the wire, inside the insulation.</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3) Electricity flows through spaces in the wire.</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>4) Electricity flows from molecule to molecule in the wire.*</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>7) No response</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1) Wires are empty of stuff that flows until it comes from the battery.</td>
<td>15</td>
<td>13</td>
<td>6</td>
<td>34</td>
</tr>
<tr>
<td>2) Wires already contain the stuff that flows.*</td>
<td>2</td>
<td>6</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>3) Undetermined as to whether stuff that flows is there already or not.</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>1) It takes energy to get through the wire.*</td>
<td>6</td>
<td>17</td>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>2) It doesn’t take energy to get through the wire.</td>
<td>6</td>
<td>2</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>3) Undetermined as to whether it takes energy to get through the wire.</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

same frequency. This is consistent with Shipstone’s (1985) observation that students tended to shift from the unipolar to the bipolar models as they got older. Shipstone also suggested that the Type 2, or the Clashing Currents model, was an intermediate step that students used or constructed after learning that it takes two wires to light the bulb (one from each end of the battery). He maintained that students still held on to the one-way flow idea and just incorporated a bipolar view of the battery. The data from this study supports this also. This is especially true in light of the fact that the seventh graders had
Table 53

Frequencies of Group 4 Responses for Model Component #7

<table>
<thead>
<tr>
<th>Component #7 – Bulbs in Series</th>
<th>6&lt;sup&gt;th&lt;/sup&gt;</th>
<th>7&lt;sup&gt;th&lt;/sup&gt;</th>
<th>8&lt;sup&gt;th&lt;/sup&gt;</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won't work because they must be hooked to battery separately.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>5</td>
<td>10</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.*</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>6) More than one predicted response used.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7) No response</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 54

Frequencies of Group 4 Responses for Model Component #8

<table>
<thead>
<tr>
<th>Component #8 – Bulbs in Parallel</th>
<th>6&lt;sup&gt;th&lt;/sup&gt;</th>
<th>7&lt;sup&gt;th&lt;/sup&gt;</th>
<th>8&lt;sup&gt;th&lt;/sup&gt;</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Won't work because they must be hooked to battery separately.</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2) Both the same as each other and the same as the single bulb.*</td>
<td>4</td>
<td>11</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>3) One bulb brighter because it gets more electricity. Both dimmer or different than single bulb.</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>4) Both the same because they get equal electricity. Both dimmer or different than single bulb.</td>
<td>12</td>
<td>8</td>
<td>6</td>
<td>26</td>
</tr>
<tr>
<td>5) Response different than predicted responses.</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6) No Response</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

recently tried making circuits that worked in class using two wires and would have incorporated this into their existing knowledge structures.
Table 55

Distribution of Model Types in Group 4 Across Grade Levels

<table>
<thead>
<tr>
<th>Grade Level</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
<th>Mixed</th>
<th>Und.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>7th</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>8th</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Totals</td>
<td>16</td>
<td>4</td>
<td>11</td>
<td>2</td>
<td>22</td>
<td>2</td>
</tr>
</tbody>
</table>

The existence of the Type 4 models in this group and in the other groups is another interesting finding that was not expected. It can be explained by students attempting to integrate the knowledge that electricity flow is round-trip, or 'in a circle', with their existing unipolar model. Obviously, this model would not stand up to experimentation since the bulb would not light and the student would be forced to try something else. This model was also found predominantly in seventh graders, 4 out of 5 overall, again showing the influence of instruction on their existing knowledge structures.
CHAPTER V

DISCUSSION

Introduction

This chapter will revisit the original research questions presented at the beginning and seek to provide answers to them. It will discuss the three kinds of mental models presented by Vosniadou & Brewer (1994) as a theoretical framework with which to view models and how this research fits into that framework. It will point out how this study adds more data to the connections between concepts and models. Lastly, future research that could proceed from this study and the broader implications of the results presented are also discussed.

Research Questions

The results of this study show that 42 of the 99 students could be assigned a coherent, detailed, well-defined mental model of electricity in a simple DC circuit. While this percentage, 42%, is lower than previous research of this type, 63% and 80% (Vosniadou & Brewer, 1992,1994), it still represents a significant number of students. Given the fact that the mental models described in this study were considerably more complex than previous studies, this result is not surprising. Looking at the previous research and combining it with this result, one can see that as the complexity of the
mental models to be described increases, from one component to four to eight, the percentage of students found using well defined mental models goes down.

Another factor that could have influenced this result is the conceptual difficulty of the topics being investigated. Vosniadou & Brewer (1992, 1994) used the shape of the earth and the day/night cycle as their content area. These topics are less conceptually complex then electricity and are areas where students have more experiential knowledge on which to start building mental models before instruction even occurs.

There were 15 different mental models found, each belonging to one of four types. The models found were consistent with previous research as described in Table 1. However, the models found in this study were described in much more detail than previous research. This increase in detail sometimes elaborated on the models already presented in previous research and sometimes contradicted them. The main difference centered around the students' conception of the nature of electricity. None of the 37 students, who were determined to have complex, well-defined mental models, described electricity as fluid-like. Previous research had indicated that some mental models contained this concept as a component of the model. So, it would appear that the nature of electricity is not a crucial component of the mental models, since so many students had the same conception of this component and still had very different mental models. Most likely this concept is not part of the main structure of the model but is, in some way, attached to it. With the exception of this concept, the rest of the models' components tended to follow the descriptions presented previously.
The 'Unipolar' Model was very evident in Models 3 & 3A. Like the 'Unipolar' Model, these models used a one-way trip flow for the Path of Flow component. Some used one wire from one end of the battery and some used two wires from one end of the battery. But, all models showed flow coming from the top of the battery to the bulb and no flow back. Some students probably felt compelled to use two wires because the bulb holder(s) had two screws. Shipstone (1984, 1985) also found some students with a 'Unipolar' Model used two wires for this same reason. In previous studies where the 'Unipolar' Model was found, students were reported as describing the battery as being full of electricity that gets emptied. That was not always the case in this study. Some students exhibited this concept (Model 3) but some thought of the battery as producing electricity (Model 3A). In previous studies, the 'Unipolar' Model described the bulb as using up the electricity to make it light. Model 3 students described the bulb lighting up because the electricity makes the filament heat up and glow. Model 3A students described the bulb as releasing electricity and making it light up. This was more like the descriptions in previous studies. So, it appears that the 'Unipolar' Model is used by some students but sometimes in slightly different forms.

The 'Clashing Currents' Model was found mostly in Models 2A, 2AB, & 2AC. These models all described the Path of Flow component as electricity flowing from both ends of the battery and meeting at the bulb. This is consistent with the 'Clashing Currents' Model found in previous studies. Model 2 also contained this same component for flow but it did not involve the "clashing" of two currents to make the bulb light. One
distinctive feature found in Models 2A, 2AB, & 2AC as well as the 'Clashing Currents' Model, is the description of positive and negative electricity flowing from the battery to the bulb and when they meet at the bulb it makes the bulb light up by combining or reacting. In previous studies, the battery was simply described as the source of electricity. This study found that even though 11 students shared similar views on the flow of electricity and the lighting of the bulb, they did not share the same view of the battery. They used one of three descriptions: (1) the battery is a passive storage tank from which the wires draw electricity, (2) the battery is full of electricity that sends it out to the bulb, and (3) the battery produces the electricity and sends it out. All the students, who used these Type 2 models, thought that the wires were empty of electricity (or the stuff that flows) before being connected and that 2 bulbs will each be dimmer than a single bulb and the same as each other when hooked in series or parallel.

The ‘Current Consumption’ Model was most like Models 1A, 1AB, & 1B. These models all share the same Path of Flow component. Round-trip from one end of the battery and back to the other. They all describe electricity as giving off all or some of its energy. Which, by the way, is what is most commonly taught in middle school science texts. In previous studies, very little description is given as to how the bulb lights. All that is mentioned is that the bulb uses up some or all of the energy or current. In the models described in this study, two different explanations emerged. First, that the bulb releases electricity as light. Second, that the electricity makes the filament in the bulb heat up and glow giving off light, the latter being the most common explanation
given. Previously, the battery was only described as being a source of current or electricity. In this study, two different explanations emerged. Both viewed the battery as being full of electricity; but one saw it as actively pushing the electricity out, and the other described a passive storage tank from which the wires draw out the electricity.

The ‘Constant Current’ Model was most similar to Model 1C & 4A, but was not exactly the same as either one of them. These models are all very similar to the 'Current Consumption' Model with the main difference being that the same amount of electricity flows back to the battery but with less energy. In the 'Current Consumption' Model less electricity flows back to the bulb than flows to the bulb. Both Models 1C & 4A use the idea that the electricity releases energy at the bulb but they use very different mechanisms to do that, none of which are described in the 'Constant Current' Model. The descriptions of how the electricity is released at the bulb were: (a) the electrons are burned at the filament releasing heat and light, (b) the filament makes the electrons give off their energy, and (c) electricity is released at the bulb making it light up. The 'Constant Current' Model, documented previously, only described the battery as supplying energy but without any explanation as to how. The two models found in this study that were most like the 'Constant Current' Model, describe the battery as recharging the electricity when it returns (Model 1C) and as being full of electricity and forcing it out through the wires (Model 4A).

The ‘Static’ or ‘Field’ Model was most evident in Model 3B but only one student exhibited this model, so its description is not as clearly defined as the others. This model
was only found in a few cases in previous studies as well (Heller & Finley, 1992). This
was one of the few models to describe electricity as pure energy. The student who used
this model described the electricity as "reacting" when it reached the bulb to produce
light. The student went on to say that this reaction caused the filament to heat up and
glow producing the light. The previous descriptions of models similar to this one were
vague and incomplete so it is difficult to say how the model found in this study actually
compares. However, it is described in much more detail in this study.

The model most similar to the 'Moving Crowd' Model was Model 1. There were
10 students who used this model, more than any other model in the study. It also is most
similar to the scientific model presented in Table 45. It uses a round-trip description to
and from both ends of the battery. The only major difference between these models and
the scientific model presented in Table 45 is whether or not the electricity makes the
round trip over and over or only once. This is a very abstract concept and is not even
discussed in most high school chemistry or physics books. The 'Moving Crowd' Model
doesn't address this issue and the students who used Model 1 in this study were not clear
on this point either. It does not appear to be a pivotal concept that determines model
structure. It seems to be a higher level concept which is attached to the model structure
after the model is constructed. Students who used this model stated that, it took energy
for the electricity to get through the wires; and, that the stuff that flows is probably
already in the wires in some way. This was consistent with previous descriptions of the
'Moving Crowd' Model.
Model 4 in this study was not documented by previous studies but appears to be a hybrid of the ‘Clashing Currents’ Model and the ‘Current Consumption’ Model. This model describes the path of flow as being round trip to and from the same end of the battery. It combines this idea with the concept of positive and negative electricity meeting at the bulb and reacting. This model appears to be Model 2AC that has been modified to include the intuitive belief that electricity only comes out of the top of the battery, like a container, and the more scientific view that electricity has to flow in a round trip.

Model 4B in this study was most like the ‘Constant Current’ Model except for the conception of the battery playing a passive role rather than an active one. Again, as with the other Type 4 models, the path of flow was described as flowing to and from the top of the battery as if it were a simple container. This shows that students, with very different descriptions of the circuits as in Models 4, 4A, & 4B; can still hold on to a very primitive and experiential view, the battery as a simple container, and that this view can greatly affect the overall structure of the model. This would also indicate that the Role of the Battery is a component that can greatly influence the overall structure of the model since many other concepts can be attached to it.

Of the students who could not be assigned detailed, well-defined mental models (n=57), 33 of them were assigned to a general model type. This was done by reducing the complexity of the model descriptions to three general characteristics: (1) type of flow, round trip or one way; (2) number of wires needed to the battery, one or two; and (3)
connections with the battery, one or both ends, one can increase the number of models found within the students’ explanations. This would imply that 75 of the 99 students were using some kind of knowledge structure consistently, albeit not always well-defined. When trying to determine whether the 33 students from Group 4, that are included in this total, are representative of a ‘mental model using’ perspective or a ‘knowledge in pieces’ perspective, it is not possible to place them in one category or the other. It appears to depend on how big or small one defines the piece(s) of knowledge being used. This group clearly did not possess a view of electricity that was structured enough to meet this study’s definition of a mental model of electricity. However, even though they did show a somewhat lower level of consistency and logical structure within their explanations than the students in Groups 1, 2, & 3, they clearly demonstrated that they were not just using pieces of knowledge at random. They tended to invoke the same small set of concepts over and over in a deliberate way. On questions that were not related to this small set of concepts, they were inconsistent in their explanations, possibly reflecting a ‘knowledge in pieces’ approach to these questions. This finding could be indicative of an incomplete or partial model or even just a smaller mental model than this study initially set out to describe. Either way, this group of 33 students appears to fall in the middle between the strict mental models perspective and the 'knowledge in pieces' perspective. This would be evidence for the existence of a continuum between the two perspectives instead of an either/or view.

When looking at the students who were assigned to the mixed model category
(n=22), they tended to switch to a different model type when answering the more complicated questions on series and parallel circuits. In many of those cases, the model type they switched to was a less scientific one. This could be due to model revising as they encounter questions that cannot be adequately answered with their existing model; or, the existence of a more complex model that has one set of components for simple circuits and another set for more complex circuits. Of course, it could also be argued that there is no model here at all and that these students are simply invoking whatever knowledge piece(s) they deem appropriate as they encounter each question. If one takes this view, then these students would be representative of a "knowledge in pieces" perspective.

In summary, almost half (42%) of the middle school students' studied possessed a knowledge of electricity that can be described using a set of 15 detailed, well-defined and internally consistent mental models that were categorized as being one of four types. These models are composed of eight different components that each represent the students' conceptions of different parts or aspects of the circuit.

Theoretical Implications

A Continuum of Students' Knowledge Structures

Since 42% of the students were found to possess detailed, well-defined mental models, this would lead one to assume that more than half (58%) must therefore possess 'knowledge in pieces' concerning electricity. However, this assumes that the debate is
an either/or proposition, instead of being a continuum. The further analysis of the students who did not meet the rigorous standards and definitions set forth by this study for the presence of mental models, showed that 33 students gave explanations that did reflect some structure. Whereas 22 students' responses showed little or no structure at all.

Therefore, in answer to the first, and most fundamental, research question presented in this study: “To what extent can middle school students' knowledge of electricity be characterized and described using a small set of well-defined mental models as opposed to a 'knowledge in pieces’ perspective?”, this researcher found evidence that supports the answer as being characterized as a continuum. A continuum from detailed, well-defined mental models to 'knowledge in pieces' with students being placed all along the spectrum from one end to the other. In other words, students' initial, intuitive knowledge appears to start out as nothing more than knowledge in pieces. It then appears to come together into loosely connected knowledge structures, that can be described generally without much detail, and could be considered simplistic mental models. These knowledge structures then become more complex and detailed and can ultimately be considered well-defined mental models as described by this and previous studies.

It appears that a number of factors affect the length of this continuum and the distribution along it:

1. The size and complexity of the knowledge structure being described.
2. The conceptual difficulty of the content area being studied.

3. The amount of experiences the student has had that utilize that knowledge.

4. The amount of time a student has had (student’s age/maturity) to process that knowledge and ‘put it together’.

Students who have barely constructed knowledge structures will tend to answer questions in logically inconsistent ways and the more incomplete their knowledge structures are the closer they will be to the 'knowledge in pieces' end of the continuum. Students who have more complete knowledge structures, i.e. mental models, will generate answers that are more logically consistent until the questions or problems exceed the limits of the structures that students have constructed to that point. These students will be closer to the other end of the continuum. Students who are somewhere in the middle will give answers that are logically consistent only to the point that the questions do not exceed the conceptual scope of their model or partial model and will take up many of the spots between both ends of this continuum.

**Three Kinds of Mental Models**

Vosniadou & Brewer (1992, 1994) use a theoretical framework of: initial models, synthetic models, and scientific models to describe the kinds models found in their studies. The models described in this study also fit into this framework. Initial models were described as “models consistent with the observations based on everyday experience.” Synthetic models were described as, “models that represent attempts to
reconcile the culturally accepted, scientific explanation with observations based on experience.” Scientific models were described as, “models which agree with the scientific view.”

The Type 1 models found in this study would be the most scientific and most frequent models found. While they may not be deemed completely scientific by a physicist’s standards, they represent a high level of scientific thinking and utilize relatively scientific conceptions for a middle school age student, given the level of science experience and instruction they have received so far.

The Type 3 models would be initial models. These models represent what students think batteries and bulbs are doing when they see them interact in everyday experiences like a flashlight. If the student hasn’t been taught how these devices work or hasn’t had a chance to explore how they work in a hands-on setting, then nothing would cause them to change this initial point of view.

The Type 2 and 4 models would be synthetic models. The Type 2 models would be a result of the student’s attempt to reconcile their existing Type 3 model, with the knowledge or observation that it takes two wires on each end of the battery to make the bulb light. Type 4 models would be a result of attempting to reconcile their Type 3 model with the knowledge that electricity flows round-trip. This fact could obviously not be an observation since students can’t actually see electricity flowing. It would have to be a fact gained through some form of instruction.

The distribution of model types in this study support this theoretical framework.
Of the 75 students identified as using a model type, 18% of the sixth graders, 27% of the seventh graders, and only 3% of the eighth graders used Type 3, or initial models. In other words, very few of the older students who have had more experience and instruction with this topic used initial models. The fact that seventh graders made up the largest group of initial model users is interesting because they had just received instruction in electricity the previous month. But, without further research into the specific instructional strategies they were exposed to, it is difficult to come up with well grounded explanations for this finding.

Secondly, 21% of the sixth graders, 27% of the seventh graders, and 15% of the eighth graders used Type 2 or 4, or synthetic models. Again, the distribution shows mostly younger students using models that have been influenced by formal or informal instruction or further experiences beyond everyday activities. Here again, the seventh graders make up the largest group which, in this case, is to be expected given their recent exposure to instruction. The older eighth grade students comprise the smallest group here but there are more of them using synthetic models than initial models. This would be expected since the older a student is the greater the likelihood that their models have been influenced by some form of instruction.

Lastly, 27% of the sixth graders, 24% of the seventh graders, and 64% of the eighth graders used Type 1, or the most scientific models. This shows that the older students, who were given instruction, had more experiences with electricity (formal and informal), and more time to process the incoming information, will tend to produce a
larger number of scientific models.

The Relationship Between Concepts and Models

Franco et al. (1999) & Norman (1983) characterized mental models as being made up of concepts and the descriptions of those mental models as being based on the descriptions of the concepts and how they are connected to each other. This study utilized this characterization of mental models and found specific examples of this theoretical framework in the form of mental models of electricity. Describing mental models of electricity as being made up of inter-related components and utilizing students’ conceptions of electricity to describe each component along with their relationship to each other to determine the type of model the students are using, is a domain-specific application of this relationship. Students were asked specific questions to determine their conception of a particular part or aspect of the electric circuit. The links between these conceptions were then plotted as the structure of the mental model only if these links were logically consistent with one another. For example, the conceptions that: electricity flows only one-way out of the top of the battery, that the battery changes the electricity from negative back into positive as it returns and sends it back out again, and that the bulb lights when the electrons gives off their energy in the bulb and go back for more are all valid and documented conceptions. However, they do not form a coherent mental model because when linked together they are logically inconsistent.

Even within the same model types, different conceptions exist that do not
radically alter the framework of the mental model. That is why some of the models were
classified in the same type. Because the basic framework of each of the models was the
same even if all the conceptions were not. It is possible, therefore, for a student to
change their conception of one part or aspect of the circuit without making a major
revision in the framework of their mental model.

Using the analogy of scaffolding to represent a mental model, some of a student's
concepts would make up the parts of the scaffolding that are the actual structure of the
scaffolding. These parts could not be removed or changed without changing the whole
structure. Other concepts would just be attached to the scaffolding but not an integral
part of the structure. These parts could be removed or changed and the overall structure
would not have to be changed.

This appears to be the case for most students with their conception of the nature
of electricity. For most students this concept appeared to be attached to the structure of
their mental model but not a major structural part. This would explain why students with
very different model structures could all have the same, very scientific, conception of the
nature of electricity. They obviously found this concept an easy one to change because
it was just attached to, or 'hanging' on, the scaffolding. However, for some models, like
Model 1C & 3B, the nature of electricity plays a much more integral role since it was
also a part of the students' explanations of the Mechanism of Action, the Role of the
Bulb, and the Role of the Battery. This concept could not be easily changed in this
model without changing the overall structure and therefore makes up a much more
significant component.

Another example of the role between concepts and model structure would be a student who changes their conception of the battery from a passive storage tank of electricity to an active storage device that pushes out the electricity. This would be a change from a less scientific conception to a more scientific one, but would not necessarily involve any changes to the rest of the structure of their model. However, if they changed their conception of the battery to a device that recharges or changes the electricity as it returns to the battery and sends it out again; they may also have to change their conception of what is happening to the electricity at the bulb and maybe even change their conception of how it flows. This type of change would involve changing a number of links between the components or the structure of the model (scaffolding); and, would therefore be considered a model revision. This would explain why so many studies in the Alternative Conceptions Movement (ACM) have documented ways of thinking that are so resistant to change even when specific concepts are targeted and changed by the researchers. What is really needed for real learning and lasting change to take place is model restructuring and revision. Being able to document students' knowledge as an inter-related knowledge structure in a detailed way, like this study has attempted to do, is a first step in determining where and how the effective changes must take place.

This study has laid some of the groundwork necessary to start bridging the gap between the mental models research domain and the ACM as described above. It has
also been shown that descriptions of students' mental models, no matter how unscientific they may be, are far richer than just identifying and listing students' alternative conceptions. As a matter of fact, many of the unscientific models of electricity described in this study are composed of some of the alternative conceptions of electricity that have been previously documented. This study also shows how some of those alternative conceptions are linked together in students' knowledge structures. It also documented one new alternative conception that electricity flows round trip to and from the same end of the battery. The models presented here also show how various scientific concepts, presented to students through instruction, are grafted into their already existing and unscientific mental models, thereby producing a large variety of hybrid models. These hybrid models consist of scientific and unscientific components used in consistent and even logical ways, to the student. This type of detailed description should be of particular interest to researchers who are evaluating various teaching methods and strategies that seek to cause conceptual change.

Measuring these changing conceptions and this type of model revising was not part of the scope of this study. It is a next logical step for research within this theoretical framework of conceptions and mental models.

Future Research

Future research using this perspective should focus on a couple of different areas. First, more work needs to be done in other content areas to describe the prevalence and
nature of students' mental models. So far this type of work has only been done in the areas of astronomy (Vosniadou & Brewer, 1992, 1994), force (Ioannides, 1991 (in Vosniadou, 1994); Ioannides & Vosniadou, 1991 (in Vosniadou, 1994), heat (Vosniadou & Kempner, 1993; Wiser & Carey, 1983), and electricity (Borges & Gilbert, 1999) along with this study. It still needs to be determined just how content-specific these findings are and how prevalent they are across science content areas.

Second, given that some students' intuitive knowledge can be described as being composed of mental models, the next step is to document model revising. More specifically, how model revising relates to conceptual change. There is already a large body of research in both these areas but very little research relating the two. If mental models are viewed as being composed of concepts, then there should be a definite relationship between these two areas of research. Also, if students' mental models can be documented in great detail, then it should be possible to engage students in various learning activities and forms of instruction and then re-document their mental models afterwards to describe specific changes.

Thirdly, once model revising and conceptual change have been more accurately described, then it should also be possible to determine which types of activities and instruction are the most effective at producing long-term changes in students' thinking in each content area.
Practical Implications

From a teacher’s point of view, this study provides some interesting thoughts on what the students who walk into their classes everyday may or may not be thinking. If one takes the conclusions presented here to heart and uses them to influence one’s pedagogy, then one has to make a variety of assumptions about their students. First of all, that for every topic or content area being covered in a typical science class there will be a wide range of knowledge structures found within each class. In other words, a teacher will most likely have students in their class that are at many different points along the continuum from 'knowledge in pieces' to detailed, well-defined mental models. So, as a first step, it is important to figure out where your students are along that continuum before launching in to a new topic.

Secondly, that some students will have a loose collection of knowledge fragments that are very disconnected no matter what topic they are covering. As a teacher, you can't assume that all your students are beyond the 'knowledge in pieces' level no matter how basic the topic is. Some teaching strategies and activities will have to be geared toward these students to help them start 'putting the pieces together' so that they can be successful at the more complicated and higher level problems and activities that involve model-using.

Thirdly, some students will have already put together some partial knowledge structures, or incomplete models, for part of the material but have put very little together concerning the rest of the material. This means that you have to determine how much
of a structure they have put together already and the form that structure takes. This can be done by questioning students in such a way so as to find out how their concepts are linked together and where their concepts are not linked to the structures they have assembled already. Questioning is the key here. The only way to make inferences about how students have or have not constructed their knowledge is to engage them in very focused questioning. Questioning designed to elicit detailed explanations of what they think is happening with each of the situations and phenomena you cover.

Fourth, that some students will have very complete and well-defined knowledge structures that are very unscientific and that these structures could be very resistant to change. Changing students' knowledge structures will probably require very different approaches than helping students build models that aren't fully constructed yet. Engaging them in discussions that involve questions like, "What do you think will happen if...." or "Why does this happen this way..." or "What do you think is going on inside this if you could see it?" should get them to start examining their own thoughts.

By letting students try out their well thought out and verbalized predictions and then talk about the results they observed; one can get students to seriously rethink the mental structures they have built and the connections between concepts that they have made.

Lastly, some students have mental models that appear very scientific at first because of the terminology they use or the problems they solve. However, further examination of those models, through detailed questioning, can reveal components that are not scientific and yet seem to work for the specific kinds of activities the student is
being asked to do. The difficult task of the teacher is to find or design activities or questions that enable students to see how incorporating a more scientific component into their mental model will help them to develop better explanations and a deeper understanding of the phenomenon they are studying.

As a science teacher and a researcher, this study has provided me with much to think about in relation to how students acquire and think about the scientific knowledge, and phenomena, that they come in contact with everyday; and how they structure that knowledge. It has definitely altered the way I approach and teach the various topics in our school’s curriculum. I am more aware of the students who have no clear cut structure or consistency to their thinking and the type of help they might need. I am also more aware of the students who have very persistent and yet, unscientific views about the world around them. It has made me rethink the types of activities in which I am engaging my students, and it has forced me to ask what each activity is asking the students to do with both the knowledge they possess and are acquiring. My students may not always appreciate the depths to which I grill them to find out what they are really thinking, but I’ve come to learn that that’s what it takes if you really want to know what they know.
Appendix A

Interview Script for Pilot Research
Mental Models of Electricity
Interview Script

Intro: Today I like to talk with you about electricity. I'm going to show you some things used with electricity like batteries, bulbs and wires and ask you some questions about them. Then I'm going to show you some diagrams of these things hooked together and ask you to tell me what you think will happen. Don't worry about whether your answers are right or wrong because nobody is going to grade them or show them to your teachers. I just want to tell me what you really think about the things I show you. Is that OK? * Do you have any questions before we start? *

While we talk about these things I'm going to turn on this tape recorder and record what we say so I can listen to it later. It will help me to better remember what we say. I might also write down some notes on these papers to help me remember later what we were talking about. Is that OK? *

OK, let's begin now. (Show subject a battery) Can you tell me what a battery does? * How does it do this? * If you could look inside the battery with special x-ray glasses what would you see happening? * What do you mean by ...? * (Ask subject to define any 'scientific' terms they used in their explanations)

(Put away the battery)

(Show subject a flashlight bulb) Can you tell me what a light bulb does? * How does it do this? * If you could see inside of all parts of the bulb with special x-ray glasses what would you see happening? * What do you mean by ...? * (Ask subject to define any new 'scientific' terms they used in their explanations)

(Put away the flashlight bulb)

(Show subject a wire) Can you tell me what a wire does? * How does it do this? * If you could see inside the wire with special x-ray glasses what would you see happening? * What do you mean by ...? * (Ask subject to define any new 'scientific' terms they used in their explanations)

(Put away the wire)

Tell me what you know about electricity. * What is electricity? * How does it work? * What do you mean by ...? * (Ask subject to define any new 'scientific' terms they used in their explanations)

(Show subject Fig. #1)
Fig. #1

Will the bulb light? *

If "NO"
Why? * Why can't the electricity get through the wire? * How can we get it to light? *

(Go to Fig. #2)

If "YES"
Why? * Describe what the electricity is doing. * How does it get to the bulb? * What is the battery doing? * How does it do this? * How does the bulb use the electricity? *

(Go to Fig. #3)
Will the bulb light? *

If "NO"
Why? * How can we get it to light? *

(Go to Fig. #3)

If "YES"

Describe what the electricity is doing at different points around the circuit at the battery, at A, at B. * What is the battery doing? * How? * How does the bulb use electricity? *

(Go to Fig. #3)

If "YES" on Fig. #1
Will this bulb be brighter, dimmer or the same as #1? * Why? * How does adding wire B affect the battery? * How does it affect the bulb? *
Will these bulbs light?

If "NO"
Why? * What needs to happen to make it light? *

(Go to Fig. #4)

If "ONE WILL"
Why? * How can we make both bulbs light?*

(Go to Fig. #5)

If "YES"
Why? * Will one bulb be brighter than the other or will they both be the same? * Why? *

Will these bulbs be brighter, dimmer or the same as the bulb in Fig. #1? * Why? *

Describe the electricity in wire A. * How does it compare with wire B? * Describe the electricity in bulb #1? * In bulb #2? * In the battery? *

(Go to Fig. #5)
Will these bulbs light? *

If "NO"
Why? * How can we get them to light? *

(Go to Fig. #5)

If "YES"
Why? * Will one be brighter than the other or will both be the same? * Why? *

Will they be brighter, dimmer, or the same as the bulb in Fig. #2? * Why? *


Are any of the wires not needed? * (If "YES" - Which one(s)? *) Why? *

(Go to Fig. #5)

If "YES" on Fig. #3
Will these bulbs be brighter, dimmer, or the same as the bulbs in Fig. #3? * Why? * How does adding wire C affect the battery? * How does it affect the bulbs? *
Will these bulbs light? *

**If "NO"**
Why? * How can we get them to light? *

(Go to Fig. #6. If Fig. #2 or Fig. #4 has not been shown yet then show them first before doing Fig. #6)

**If "ONE WILL"**
Why? * How can we get them both to light? * Describe the electricity in wire A? * In wire B? * In wire C? *

(Go to Fig. #6. If Fig. #2 or Fig. #4 has not been shown yet then show them first before doing Fig. #6)

**If "YES"**
Why? * Will one be brighter than the other or will both be the same? * Why? *

Will they be brighter, dimmer, or the same as the bulbs in Fig. #3? * Why? * What about the bulb in Fig. #1? * Why? *


(Go back and do Fig. #2, Fig. #4, and then Fig. #6)
Will these bulbs light?

If "NO"
  Why? * How can we get them to light? *

If "ONE WILL"
  Why? * How can we get them both to light? * Describe the electricity in each of the 6 wires lettered on the diagram. *

If "YES"
  Why? * Will one be brighter than the other or will both be the same? * Why? *

Will they be brighter, dimmer, or the same as the bulbs in Fig. #4? * Why? * What about the bulb in Fig. #2? * Why? *

Describe the electricity in each of the 6 wires lettered on the diagram. * describe what is happening in each of the bulbs. * In the battery. *

Are any wires not needed? * Why? *

If "YES" on Fig. #5

Will these bulbs be brighter, dimmer, or the same as the bulbs in Fig. #5? * Why? * How does adding wires D, E, & F affect the battery? * How does it affect the bulbs? *
Appendix B

Electricity Survey
Thank you for filling out this survey. Please do one page at a time. Once you finish a page go on to the next page. DO NOT GO BACK AND CHANGE ANY ANSWERS TO ANY QUESTIONS ONCE YOU HAVE FINISHED THAT QUESTION. Please try to answer every question even if you have to guess!!!

1) Please circle the grade you are in this year: 6 7 8 9

2) I am ______ years old and I am a (circle one) Male  Female

3) Did you study electricity, batteries or light bulbs this year in school? Yes No

4) If YES, how long ago was it when you studied these topics? ______________

**PART 1**

Below is a drawing of a battery and a light bulb. Use a pencil or pen to draw the wire or wires necessary to make the bulb light. Be sure to make the line or lines you draw touch the battery and the bulb exactly where they need to touch to make the bulb light.

5) Draw arrows on the diagram to show how the electricity moves when the bulb lights.

6) If you could see the electricity flowing in a wire close up, what would it look like? Draw your answer and explain it in writing.
PART 2

Please indicate whether the bulb will or won't light the way it is drawn.

7) Circle one:
   WILL LIGHT
   (Explain why below)
   WON'T LIGHT
   (Explain why not below)

8) If you circled "WILL LIGHT", draw arrows on the wire(s) indicating which way the electricity will move.

If you circled "WON'T LIGHT" fix the drawing by adding or changing whatever is necessary to make it light and then draw arrows on the wire(s) indicating which way the electricity will move.
Please indicate whether the bulbs will or won't light the way it is drawn.

9) Circle one:  
- WILL LIGHT  
  (Explain why below)  
- WON'T LIGHT  
  (Explain why not below)

10) If you circled "WILL LIGHT", draw arrows on the wire(s) indicating which way the electricity will move.

    If you circled "WON'T LIGHT" fix the drawing by adding or changing whatever is necessary to make it light and then draw arrows on the wire(s) indicating which way the electricity will move.

11) Will these bulbs be the same brightness as each other? Why or why not?

12) Will these bulbs be the same brightness as Figure #1? Why or Why not?
Please indicate whether the bulbs will or won't light the way it is drawn.

13) Circle one:  

WILL LIGHT  
(Explain why below)  

WON'T LIGHT  
(Explain why not below)

14) If you circled "WILL LIGHT", draw arrows on the wire(s) indicating which way the electricity will move.

If you circled "WON'T LIGHT" fix the drawing by adding or changing whatever is necessary to make it light and then draw arrows on the wire(s) indicating which way the electricity will move.

15) Will these bulbs be the same brightness as each other? Why or why not?

16) Will these bulbs be the same brightness as Figure #1? Why or Why not?
17) On the enlarged diagram of the light bulb below, draw and explain what the electricity does inside the bulb that causes it to light up.

18) On the enlarged diagram of the battery below, draw and explain what the electricity is doing inside the battery when it is making the bulb light up.
PART 3

Read each statement below carefully and pick the one statement (or more than one) that you think best describes electricity.

19) When a battery is hooked up to a bulb:

A) Electricity flows out one end of the battery to the bulb and then back again to the other end, but it only makes the trip once.

B) Electricity flows out both ends of the battery and meets at the bulb.

C) Electricity only flows from one end of the battery to the bulb and is used up at the bulb.

D) Electricity flows out one end of the battery to the bulb and then back to the other end of the battery, then it keeps repeating the same trip over and over.

E) I don’t agree with any of them because ________________________________

F) I circled more than one of them because ________________________________

20) A battery can make a bulb light up because:

A) Negative electricity flows from one end of the battery and positive electricity flows from the other end of the battery, when they meet at the bulb they react and form light.

B) Once electricity reaches the bulb it reacts to form light and is changed into something different.

C) When the electricity reaches the bulb it is released as light by the little wires in the bulb and there is nothing left.

D) When electricity reaches the bulb it gives off some of its energy and goes back to the battery.

E) When electricity reaches the bulb it gives off all its energy and goes back to the battery.

F) I don’t agree with any of them because ________________________________

G) I circled more than one of them because ________________________________
21) A battery works because:

A) The battery is full of electricity when it is fresh and the wire(s) pull the electricity out of the battery until the battery is empty.

B) The battery makes electricity inside it and sends it out through the wire(s) to the bulb.

C) The battery is full of electricity when it is fresh and keeps pushing the electricity out through the wire(s) until it is empty.

D) The battery recharges or makes the electricity usable again when it returns. The battery sends it back out again.

E) I don't agree with any of them because

F) I circled more than one of them because

22) I think the best description of electricity is:

A) Electricity is a liquid.

B) Electricity is moving particles.

C) Electricity is moving particles that carry energy with them.

D) Electricity is not a substance, it is pure energy.

E) I don't agree with any of them because

F) I circled more than one of them because
23) **Electricity can go through wires because:**

A) Electricity flows through wires just like water flows through a straw.

B) Electricity flows on the outside of wires but inside the plastic coating.

C) Electricity flows through the spaces between the molecules inside the wire.

D) Electricity flows from molecule to molecule inside the wire.

E) I don't agree with any of them because ___________________________

F) I circled more than one of them because ___________________________

---

For questions 24-30 indicate whether you agree, disagree or are not sure and explain your answer in the space provided.

24) **It takes energy for the electricity to get through the wire.**

A) I agree because ___________________________

B) I disagree because ___________________________

C) I'm not sure because ___________________________

---

25) **Wires contain electricity in them before they are hooked up it just doesn't flow until the battery pushes it.**

A) I agree because ___________________________

B) I disagree because ___________________________

C) I'm not sure because ___________________________
26) **Wires are empty of electricity until they are connected to the battery.**

A) I agree because ____________________________

B) I disagree because ___________________________

C) I'm not sure because _________________________

27) **One battery can only make one bulb light up.**

A) I agree because ____________________________

B) I disagree because ___________________________

C) I'm not sure because _________________________

28) **Electricity can flow in two directions at the same time in the same wire.**

A) I agree because ____________________________

B) I disagree because ___________________________

C) I'm not sure because _________________________
29) Electricity gives off its energy in the bulb because it is so difficult to get through the small wires in the bulb. This makes the wires heat up and glow and give off light.

A) I agree because ____________________________________________________________

B) I disagree because ________________________________________________________

C) I’m not sure because _______________________________________________________

30) The battery's job is to push the electricity through the wires.

A) I agree because ____________________________________________________________

B) I disagree because ________________________________________________________

C) I’m not sure because _______________________________________________________

Appendix C

Survey Scoring Sheet
Survey Scoring Sheet

<table>
<thead>
<tr>
<th>Grade</th>
<th>Age</th>
<th>M or F</th>
<th>Study electricity this year? Y or N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**How long since you studied these topics?**

**Component #1 - Nature of Electricity (Descriptive) - What is electricity? 6,22**

<table>
<thead>
<tr>
<th>1) Electricity is a fluid (liquid or gas). 22A</th>
<th>2) Electricity is pure energy, not a substance, like light or heat. 22D</th>
<th>3) Electricity is moving particles. 22B</th>
<th>4) Electricity is energy carried by moving particles. 22C</th>
</tr>
</thead>
</table>

**Component #2 - Path of Flow (Descriptive) - How does electricity flow? 5,7,8,9,10,13,14,19,20,27,28**

<table>
<thead>
<tr>
<th>1) Flow in one direction only from one end of the battery, a one-way trip. 19C</th>
<th>2) One-way trip but must flow from both ends of the battery. Both wires needed. Can flow in two directions at once in some wires. 19B, 20A</th>
<th>3) Round trip flow in one direction, both wires needed. Electricity makes the trip over and over, out one end and in the other. 19D</th>
<th>4) Round trip flow in one direction, both wires needed. Electricity only makes the trip once. 19A</th>
</tr>
</thead>
</table>

**Component #3 - Mechanism of Action (Explanatory) - How does electricity work? 19,20**

<table>
<thead>
<tr>
<th>1) Electricity flows from the battery to the device and is used up. 20C</th>
<th>2) Electricity has two parts, (+ &amp; -), both come from battery and combine in device to make it work. Both are used up. 19B, 20A</th>
<th>3) Electricity flows to device where some of its energy is used up, the rest flows back to the battery. 20D</th>
<th>4) Electricity flows to the device and gives off all its energy then flows back to the battery. 20E</th>
</tr>
</thead>
</table>

**Component #4 - Role of the Battery (Explanatory) - How does a battery work? 18,21,25,30**

| 1) Passive - is full of electricity and gets emptied as it is used, when it is empty it is dead. Device or wires draw electricity out, like a storage tank. 21A, 30B | 2) Active - is full of electricity and gets emptied as it is used, when it is empty it is dead. Battery forces electricity out. 21C, 30A | 3) Active - only pushes electricity around, pumps-like, when it is unable to push the electricity it is dead. 21E, 30A | 4) Active - it recharges or changes the electricity that returns to the battery and then sends it out again. When it is unable to recharge it is dead. 21D, 30A | 5) Active - produces electricity inside it when it is no longer able to produce it, it is dead. Battery forces electricity out. 21B, 30A |
Component #5 - Role of the Bulb (Explanatory) - How does a bulb work? 17, 20, 29

| 1) Electricity is released by the wires in the bulb causing light. 17, 20C | 2) Both types of electricity, (+ & -), combine in bulb and react or explode causing light and heat. 17, 20A | 3) Electricity flows to bulb, reacts or changes, gives off light and heat (and maybe waste products). 17, 20B | 4) Electricity gives off energy as it flows through little wires and causes them to heat up and glow and give off light. 17, 29A |

Component #6 - Role of the Wires (Explanatory) – How does electricity get through the wires? 6, 23, 24, 25, 26, 28, 29

| 1) Lets electricity flow through like tubes. 23A | 2) Electricity flows on the outside of the wire, inside the insulation. 23B | 3) Electricity flows through spaces in the wire. 23C | 4) Electricity flows from molecule to molecule in the wire. 23D |
| 1) Wires are empty of stuff that flows until it comes from the battery. 25B, 26A | 2) Wires already contain the stuff that flows. 25A, 26B |
| 1) It takes energy to get through the wires. 24A | 2) It doesn’t take energy to get through the wires. 24B |

Component #7 - Bulbs in Series (Predictive) - Which bulb will be brighter? 11, 12, 27

| 1) Won’t work because they must be hooked to battery separately. | 2) Both the same as each other and the same as the single bulb. | 3) One bulb brighter because it gets more electricity. Both dimmer than single bulb. | 4) Both the same because they get equal electricity. Both dimmer than single bulb. |

Component #8 - Bulbs in Parallel (Predictive) - Which bulb will be brighter? 15, 16, 27

| 1) Won’t work because they must be hooked to battery separately. | 2) Both the same as each other and the same as the single bulb. | 3) One bulb brighter because it gets more electricity. Both dimmer than single bulb. | 4) Both the same because they get equal electricity. Both dimmer than single bulb. |
Appendix D

Informed Consent Forms
Dear Parents,

My name is Drew Isola. I am currently working on a dissertation project in Science Education at Western Michigan University. Because I have been, and will continue to be, a teacher in the Allegan Public Schools district; I have requested and received permission from the district to do a research project with APS student volunteers. My project involves documenting the conceptions and theories students hold about electricity and how it works. This will involve interviewing a number of students about what ideas they hold of electricity.

Your son/daughter has expressed an interest in being involved in this project. I have explained my project to them and told them that they need to get permission from you before they can participate. The following pages are the necessary consent forms for you and your child to sign. They explain in more detail the nature of the project and what your child’s involvement would be if you agreed to their participation.

If you have any questions please feel free to call me at 673-3793.

Thank You,

Drew Isola
CHILD CONSENT FORM

Western Michigan University
Department of Science Studies

Principal Investigator: Dr. Robert Hafner
Research Associate: Drew Isola

I understand that I have been asked to participate in a research project entitled "Students' Mental Models of Electricity." The purpose of this study is to explore and describe the different ideas and theories that students have about what electricity is and how it works.

I understand that if I agree to participate, I will be interviewed for about an hour on the subject of electricity and that interview will be audio taped. I understand that if I choose to participate my grade in school will not be affected. I also understand that if I choose not to participate my grade will also not be affected. Even if I agree today to participate by signing this form, I can change my mind at any time before the interview or even during the interview. If I do change my mind my grade will not be affected and no one will be upset with me.

I understand that my name will not be on any tapes or papers and the you will use a code number instead. You will keep a list of names and code numbers separate from the tapes and that will be destroyed once you have finished the research project.

If I have any questions or concerns about this study, I may contact either Dr. Robert Hafner at 387-5844 or Drew Isola at 673-3793. My signature below indicates that I understand the purpose and methods of the study and that I agree to participate.

Print name here

Sign name here 

Today's Date
PARENT OR GUARDIAN CONSENT FORM

Western Michigan University
Department of Science Studies

Principal Investigator: Dr. Robert Hafner

Research Associate: Drew Isola

I understand that my child has been invited to participate in a research project entitled "Students' Mental Models of Electricity." The purpose of this study is to describe the different conceptions and theories that students have about the nature of electricity and how it works in simple circuits. I further understand that the purpose of this project is to fulfill Drew Isola's dissertation requirement.

My consent for my child to participate in this project means that my child will be interviewed about their knowledge and ideas of electricity. This interview will take about an hour. During the interview students will be shown batteries, bulbs, and wires and asked to give explanations on how they work. Students will also be shown diagrams of circuits and asked to predict if the circuit will work or not and explain why they made these predictions. Students will not work with actual circuits involving electric current.

I understand that these interviews will be audio taped and that, although no sensitive information is being recorded, the information collected is confidential. My child's name will not appear on any audio tapes, transcripts, or reports and articles generated from this data. Subjects will be identified by a reference number and a master list that shows the corresponding names will be kept separately from the data. This master list will be destroyed, along with the tapes, at least 3 years after the project is completed. Until that time all collected information will be retained in Dr. Robert Hafner's files.

I understand that my child is free at any time - even during the interview - to chose not to participate. If my child refuses or quits, there will be no negative effect on her/his school programming and no negative feedback or comments from the researcher or my child's teachers. Students will not be graded or evaluated in any way as a result of this activity and students' teachers will not be notified of any individual's responses or have access to any of the audio tapes of the interviews.

I understand that no risks, hazards, or discomforts are foreseen as a consequence of this study. As in all research, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to the subject except as otherwise stated in this consent form.

I understand that while there are no intended immediate benefits to my child for participating, there may be benefits to science teachers in general and their students since the results of this study could increase teachers' understanding of students' prior knowledge of electricity.

I understand that I may also withdraw my child from this study at any time without any penalty or prejudice. If I have any questions or concerns about this study, I may contact either Dr. Robert Hafner at 387-5844 or Drew Isola at 673-3793. I may also contact the Chair of Human Subjects Institutional Review Board at 387-8293 or the Vice President for Research at 387-9298 with any concerns that I have.

My signature below indicates that I understand the purpose and requirements of the study and that I give my permission for ______________________ (child's name) to participate.

Parent or Guardian Signature

Date

Phone number where parent can be most easily reached
Appendix E

Protocol Clearance From the Human Subjects
Institutional Review Board
Date: March 19, 1996

To: Drew Isola

From: Richard Wright, Chair

Re: HSIRB Project Number 96-03-17

This letter will serve as confirmation that your research project entitled “Student’s mental models of electricity” has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you must seek specific approval for any changes in this design. You must also seek reapproval if the project extends beyond the termination date. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: March 19, 1997

xc: Robert Hafner
BIBLIOGRAPHY


Franco, C., Krapas, S., Queiroz, G. & Alves, F. (1999). From scientists’ and
inventors’ minds to some scientific and technological products: relationships between theories, models, mental models and conceptions. *International Journal of Science Education*, 21(3), 227-291.


