Students' Conceptual Modeling of Simple DC Electric Circuits

During Computer-Based Instruction

by

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ABSTRACT
A dynamic research strategy was employed to track the development of mental models of simple DC circuits and reasoning patterns of students learning these concepts for the first time. The medium for research and instruction was a computer tutorial that allowed students to explore their ideas and beliefs as they manipulated simple materials. The study utilized structured observations generated from videotaped data and transcribed analysis of students' verbal commentaries. Verbal protocol analysis (Ericsson and Simon, 1994) provided data for the development of conceptual maps (Dykstra, Boyle, and Monarch, 1992) from which students' conceptual frameworks and mental models were inferred. The sequence and types of changes the models underwent were illustrated by the changes in the conceptual maps as the subjects progressed from a naive understanding towards a more scientific understanding.

Both assimilation and accommodation occurred to different degrees: from the acquisition of a single, simple idea (or separation of a single, minor idea) to the development of elaborate and inter-related ideas. In both cases, the process was not simple nor straightforward. Rather, the process is better described as a painful negotiation and renegotiation of conflicting beliefs. The "path" from naive towards expert understanding goes in both directions, with subjects moving backward (toward personal theories) as easily, if not more so, as forward (toward expert understanding).

Studying conceptual change in physics learning is necessary in order to develop appropriate instructional materials and strategies that take into account students' preconceptions and how those preconceptions change during instruction.
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Chapter 1
INTRODUCTION

The purpose of this study was to track the development of mental models of simple DC circuits and reasoning patterns of students learning these concepts for the first time. The medium for research and instruction was a computer tutorial that allowed students to explore their ideas and beliefs as they manipulated simple materials. The students worked in pairs to develop explanations of circuit phenomena that they were then challenged to test, evaluate, and revise.

Statement of Problem

Although there has been considerable investigation of students' alternative frameworks, there is currently no well-articulated theory that describes the process in which one set of concepts change to another set that was incompatible with the first (Posner, Strike, Hewson, & Gertzog, 1982). Smith (1991) argues that (1) studies contrasting students' naive conceptions to scientific theories, (2) cognitive theories of conceptual understanding and knowledge structures, and (3) models of conceptual change are useful in characterizing what cognitive changes need to occur for learning to take place, but are less helpful in characterizing how the process of conceptual change can be promoted. This study specifically focused on documenting the changes that occurred in students' conceptual frameworks and mental models as they progressed through a series of inquiry-based activities.
Rationale for Study

Studying conceptual change in physics learning is necessary because students come to class with firmly held and useful, alternative conceptions that differ from scientific ones. Traditional textbooks and methods typically do not address students' alternative frameworks and most students complete a physics course with their conceptual frameworks essentially unchanged. In other words, conceptual understanding, where students construct their own knowledge, does not occur even though students can successfully solve computational problems in physics.

The problem arises when instruction simply presents students with concepts. This mode does not promote conceptual understanding because the information makes little sense to students given their existing frameworks. Conceptual understanding occurs when students construct meaning from their currently held beliefs. Therefore, an understanding of alternative conceptions and appropriate instructional strategies are necessary before conceptual understanding can be promoted. Instructional strategies that force students to challenge their beliefs include the learning cycle as proposed by Karplus (1980), microcomputer-based laboratory experiences developed by Thornton (1987), disequilibration techniques as proposed by Minstrell (1989), and bridging analogies as developed by Clement (1993). The next step is to provide experiences that promote reconstruction of conceptual frameworks, progressing students from their naive stage towards a so-called expert stage congruent with current scientific beliefs.

The process of conceptual change from naive to expert has not been adequately described. Although the differences between novice and expert
understanding is well documented, Ledbetter (1993, p. 611) states “Few researchers have scrutinized the constructions that science students create.” In other words, what occurs as students progress from novice to expert is not well documented. Dykstra, Boyle, & Monarch (1992) propose that there are various kinds and degrees of conceptual change, and that it is necessary to explicitly represent students’ alternative conceptions at each stage of developing understanding in order to determine the appropriate instructional strategies. Conceptual change begins with an understanding of the students’ alternative frameworks, their naive conceptions, that are demonstrated by their difficulties with new concepts. The difficulties students have with electric circuits are a prime example.

To understand the concepts and phenomena underlying the domain of electricity and, more specifically, simple electric circuits, students need to explore in a qualitative fashion and reason about phenomena without relying on equations and formulae that are often used as crutches. Arons (1982) terms this type of qualitative reasoning phenomenological reasoning and asserts students do not have enough opportunity to engage in it. He also maintains that students need to practice phenomenological reasoning in order to conceptually understand a phenomena. He goes on to state that “An area in which most students are very much in need of help with phenomenological reasoning is that of elementary resistive direct-current circuits.” (p.15).

Summarizing from current research, an appropriate instructional sequence to promote conceptual understanding would: (a) begin with students' existing alternative frameworks; (b) engage students in situations where they are forced to challenge their existing frameworks through, for example,
disequilibrating experiences; (c) build from students' existing frameworks by making the new information sensible through such strategies as analogies; and (d) involve the students in a series of hands-on and minds-on experiences that allow them to construct and reconstruct progressively more sophisticated mental models.

For the teaching of electric circuits, such an instructional sequence would closely follow the programs developed by Arons (1990) and Shaffer and McDermott (1992). The instruction would make use of appropriate analogies and strategies from the Teaching-with-Analogies model (Glynn, 1991) and the Bridging-Analogies model (Clement, 1993). In addition, the instruction would provide students with simple materials such as batteries, flashlight bulbs, and wire, to test and explore their ideas, concepts, and models. The instruction would also take advantage of computers as an interactive media that can promote understanding through simulations and inquiry-based learning. Computers can assist the development of appropriate instructional strategies by recording how the student interacts with the program.

Computers can not only facilitate learning, but if used properly, computers can aid research in how conceptual understanding develops. Krajcik, Simmons, & Lunetta (1988) used what they termed a dynamic research strategy that involved structured observations of students interacting with concepts presented via instructional software. According to the researchers, "Structured observations are related to naturalistic methods and are distinct from experimental research strategies" (p. 149). Techniques of structured observations

1Hands-on experiences involve the manipulation of materials, like batteries, bulbs, and wire. However, there is no assurance that simply manipulating materials promotes critical thinking and problem solving. Minds-on experiences denotes manipulative experiences that do promote critical thinking through, for example, peer dialogue.
have allowed the investigation of how students (a) develop concepts, (b) interact with instructional software, and (c) solve problems.

**Research Design**

The research design for this exploratory study utilized a naturalistic research methodology to examine the development of mental models and reasoning patterns of pairs of students interacting with a computer tutorial that utilized an inquiry format and involved manipulation of simple materials. The design included:

1. The administration of a pre-instructional assessment to determine students’ prior knowledge of simple DC circuits;
2. An instructional activity incorporating analogies presented by an interactive computer program and included the use of simple materials such as batteries, wire, and flashlight bulbs;
3. Structured observations of pairs of students interacting with the computer tutorial, the materials, and with each other; and
4. The administration of a post-instructional assessment to determine the students’ understanding of electric circuits after instruction.

A VCR was connected to the computer video output to record the interaction with the tutorial. A video camcorder recorded the students’ interaction with each other. To assure that their verbal responses were captured clearly, an audiorocassette recorder with separate microphone was employed.

Verbal protocol analysis (Ericsson and Simon, 1993) provided data for the development of conceptual maps (Dykstra, Boyle, and Monarch, 1992) from which students’ conceptual frameworks and mental models were inferred.
Written observations by the researcher and notes made by the students supplemented the protocol data.

The principal objectives of this study were to identify the: (a) concepts and conceptual relationships that comprise students' mental models; (b) sequence of changes the models undergo; and (c) types of changes the mental models undergo as students acquire better understanding. Secondary objectives of the study were to follow students' reasoning patterns and their influence on the process of conceptual change. Given these purposes, a dynamic research design as described by Krajcik, Simmons, and Lunetta (1988) was selected as the framework for the study (see also, Erickson, 1984; Holstein & Gubrium, 1994; and Fischer & Aufschanter, 1993). Their design involved structured observations of a student interacting with a genetics computer simulation.

By examining, in detail, the conceptual changes that occur as students attempt to understand material that is contradictory to their personal experiences, educators will obtain a better understanding of how students learn. In particular, conclusions from the study will assist educators in developing appropriate instructional strategies that target students' interim mental models, as well as provide information on the processes and changes that occur as students progress from naive towards expert levels of understanding. The information obtained will provide an example of conceptual change learning for teachers and other educators.
Chapter 2

REVIEW OF LITERATURE

Introduction

Science education research should inform educators, teachers, and curriculum developers of new insights and understandings into the nature of the learner, the process of learning, and instructional strategies that promote scientific literacy in students. According to Project 2061, a scientifically literate person (a) is aware that science, mathematics, and technology are interdependent human enterprises; (b) understands key concepts and principles of science; (c) is familiar with the natural world; and (d) uses scientific knowledge and scientific ways of thinking (Rutherford & Ahlgren, 1989).

The nature of science precludes the memorization of specific content: science is a process for producing knowledge; therefore, it is a body of knowledge that is continually changing and growing (Rutherford & Ahlgren, 1989). Acquiring scientific literacy means that students must become life-long learners. They need to be able to qualitatively understand concepts and “students who understand the process [of science] are better prepared to acquire science content on their own” (Glynn, Yeany, & Britton, 1991, p. 3). Science is also considered a social enterprise, taking place within a variety of social contexts.

Carey and Smith (1993) maintain that scientific knowledge is misrepresented in most science classrooms: scientific knowledge is portrayed as arising solely from the data about the world, compared to a more constructive epistemology where scientists hold personal theories that guide interpretation and generation of specific hypotheses and experiments. More simply put,
scientific theories arise from personal interpretative frameworks, a notion that parallels current theories of learning as a process of changing personal conceptual frameworks.

Theories of teaching and learning are constantly evolving. Students were once viewed as tabula rasa where learning occurred solely through the senses and experiences, which were written on the blank slate of the mind. Bruner (1985) described other models of the learner including the hypothesis generator where experiences were shaped by the learner through their intentions, language, or beliefs, and nativism where learning is dependent on the innate structure and powers of the mind. As our models of the learner change, so do our models of teaching.

Traditional textbooks and methods do not take into account current theories of learning, specifically the role of prior knowledge and alternative conceptions, and the nature and influence of students' mental models. Traditional instruction and curricula tend to be based on the "absorption" view of teaching and learning. Students passively absorb knowledge invented by others and recorded in texts or known by authoritative adults (Clements & Battista, 1990). Glynn and his colleagues (Glynn, Yeany, & Britton, 1991) describe how science curricula can be placed on a continuum from textbook-centered to teacher-centered. A textbook-centered curriculum is one in which the curriculum is driven by the textbook, and, for some, considered to be teacher-proof or at least designed to support a teacher who may lack important knowledge, skills, or experience. In the teacher-centered curriculum, the textbook can still play an important role, however, it is the teacher who controls the instructional methods. This curriculum assumes that the teacher knows a
great deal about science, instructional methods, learning theories, and student
development. Unfortunately, U. S. science curricula tend to be textbook-
centered, and according to the American Association for the Advancement of
Science report, *Science for All Americans*:

The present science textbooks and methods of instruction, far from
helping, often actually impede progress towards scientific literacy.
They emphasize the learning of answers more than the exploration
of questions, memory at the expense of critical thought, bits and
pieces of information instead of understandings in context,
recitation over argument, reading in lieu of doing. They fail to
encourage students to work together, to share ideas and
information freely with each other, or to use modern instruments to
extend their intellectual capabilities. (Rutherford & Ahlgren, 1989,
p. 14)

When students are taught as if science is a body of knowledge to be
memorized and equations to be used mechanically, they fail to develop
qualitative, conceptual understanding of the concepts and principles. As a result,
students leave the science classroom not able to apply or even see the
relationship of science to problems in their everyday lives. In addition, students
are not provided the opportunity to develop such skills as problems solving,
critical thinking, and learning how to learn.

Current theories of learning describe students as actively constructing
knowledge by building upon existing knowledge, through hands-on experiences,
and in cooperative social settings. Constructivism, in its most simple form, states
that the learner actively constructs meaning and understanding. Learning is
viewed as the development of conceptual understanding and not a function of
students' abilities to memorize and repeat information. Students' conceptual
frameworks are an important aspect of constructivism that were not part of the
traditional empiristic and positivistic notions of teaching and learning (Duit, 1991a). Conceptual frameworks were not as important in the "models" discussed by Bruner (1985). Constructivism grew out of the work of Ausbel, Piaget, Kelly, and Vygotsky, among others. Constructivist theories attempt to provide explanations for observed student behavior and interaction as well as a rationale for the design of instruction.

**Constructivist Theories Of Learning**

Constructivism, simply put, states that the learner actively constructs meaning and understanding. According to Champagne and Bunce (1991), science teaching should be based on learning theory that addresses the following five principles:

1) scientific knowledge is complex,
2) experts' knowledge is tacit (understood without being openly expressed),
3) learner's construct understanding,
4) personal/prior knowledge influences learning, and
5) social interaction produces cognitive change.

Learning science involves more than acquiring a working vocabulary and the ability to manipulate equations. Scientific knowledge is a complex body of interrelated concepts, principles, and ideas that change as greater understanding is developed. Often the relationships are not explicitly recognized by the student or by the expert. Understanding occurs at different levels, sometimes masking whether true understanding has occurred. Experts' knowledge is often tacit
making the teaching of science even more difficult: it is hard to teach what you
do not know you need to teach.

Constructivism recognizes the importance of having students as active
participants in the learning process. Learning is viewed as an active and
complex process of acquiring new knowledge and making sense of new
information and new experiences. This complex process involves the interaction
of many cognitive processes such as perception, imagery, memory, organization,
and elaboration. Research on how students develop conceptions in physics
(McCloskey, 1983; Smith, Carey, & Wiser, 1986; Viennot, 1979; Wiser & Carey,
1983) support this view. In addition, research in other disciplines such as biology
(Carey, 1985) and astronomy (Vosniadou & Brewer, 1987) provide further
evidence of the constructivist nature of learning.

A student’s prior knowledge, expectations, and preconceptions play an
important role in determining what the student attends to and therefore learns.
According to Glynn and his colleagues (Glynn, Yeany, & Britton, 1991), as
students reason scientifically, utilizing facts, principles, and skills stored in long-
term memory, the resulting products produced in working memory are the
students’ own personal beliefs, theories, and models. Existing knowledge may
facilitate or impede this process. Champagne and Bunce (1991, p. 29) describe
the situation quite well:

Most formal science instruction imparts scientific theories
without any regard for the students’ spontaneous [personal]
theories. When the tenets of the scientific theories conflict
with spontaneous theories or describe a world that does not
fit with the students’ personal experience, they are rejected
outright or accepted as theories that apply only in the
context of formal science and are useful only to the extent
that they are interesting or are necessary to achieve a good
grade in the course.
Social constructivism attempts to circumvent this situation by bringing students together in social contexts that involve their active participation in examining and challenging what they know, to refine and build upon their knowledge. Initially proposed by Vygotsky (1978), social constructivism relies heavily on the use of language and its function in promoting understanding in social contexts. Its central premise is that students are actively involved in constructing meaning through language during social interactions. Different forms of language use are emphasized to facilitate meaning construction. Such forms include open-ended questions, discussions, students' explanations, and creative writing (Glasson & Lalik, 1993).

Social interaction produces cognitive change because cognitive abilities are socially transmitted, socially constrained, socially nurtured, and socially encouraged (Champagne & Bunce, 1991). Social interactions between peers is as important as interactions with the teacher (if not more so). Appropriate social interactions provide mechanisms in which student-student communication, exploration, and discovery are enhanced. As students talk among themselves, they tend to use simpler language, are able to spot inconsistencies quicker, and understanding has the potential to develop faster. The closer a new idea is to an existing one, the easier its assimilation will be. This is, of course, why analogies can be so effective. Analogies and metaphors are part of language use and are often crucial in constructing understanding. They are used spontaneously by scientists and science students as a natural part of learning. Analogies allow individuals to share complex concepts in simple, straightforward language that others can relate to.
In sum, constructivist learning involves a process of construction and reconstruction of personal knowledge that involves changing conceptual frameworks. To understand the difficulty inherent in changing conceptual frameworks, (a) the nature of conceptual frameworks, (b) the role of mental models, and (c) the importance of personal models will be discussed. The last sections examine conceptual change learning and teaching, and the role of analogies specifically pertaining to learning about simple DC electric circuits.

**Conceptual Frameworks**

Conceptual frameworks, cognitive structures, belief systems, and conceptualizations are some of the ways we attempt to describe the sense-making efforts of students. Conceptual frameworks represent the organization of knowledge acquired from personal experiences resulting from informal interaction with the physical and social environment as well as through formal interaction within the school environment (Pines & West, 1986b). Conceptual framework refers to the arrangement and organization of an individual's ideas, meanings, and concepts that is the basis for understanding; understanding that is dependent on the relationships that exist among the ideas, meanings, and concepts (Pines, 1985).

Students' conceptual frameworks are not collections of isolated undefined ideas; rather, these frameworks consist of conceptions that are organized in a fairly coherent manner, although limited in their applicability and utility (Duit, 1991a). Since relations are the key to meaning and the development of understanding, difficulty arises with the nature of those relations. Concepts may have different meanings in different situations; that is, according to Pines (1985, p. 109), "a single concept may mean one thing within one framework and
something slightly different within another context” depending on the relations that exist. Misconceptions are ideas and beliefs held by the student based on personal experiences that are incomplete and inconsistent with accepted scientific explanations. A so-called “misconception” results when the student acquires an inappropriate conceptual relation within a certain context. Misconceptions, therefore, do not exist independently but are part of existing conceptual frameworks.

Students' prior knowledge is also described by such terms as alternative conceptions, alternative frameworks, spontaneous theories, personal theories, as well as misconceptions. The term misconception has negative connotations that misrepresents the constructivist nature of learning. Misconceptions are not necessarily conceptions that are wrong. Misconceptions, or perhaps more appropriately, personal conceptions are an integral part of existing conceptual frameworks and play an important role in the learning process. Often these personal conceptions form important mental models that students use to guide further understanding. Mental models are important in science teaching and learning because the development of conceptual understanding involves the reconstruction of students' personal mental models.

**Mental Models**

Mental models are collections of ideas and beliefs based on informal and formal knowledge that is used to explain phenomena. According to Redish (1994), mental models consist of propositions, images, rules of procedure, and statements as to when and how to use them. Mental models are continually evolving as the individual interacts with new concepts and new situations (Norman, 1985). Mental models are sometimes referred to as students'
representations of situations or phenomena. They begin as naive notions that are considered primitive in that they stand without significant explanation. They are based almost solely on experiences and observations. Naive physics students begin with a rich but non-hierarchical collection of recognizable phenomena based on their observation. These so-called phenomenological primitives, or p-prims\(^2\), are the beginnings of mental models (diSessa, 1985).

Mental models do serve some functionality even though they are not completely accurate; however, students' ability to use them may be severely limited. Mental models may contain contradictory elements and are typically incomplete. Furthermore, mental models do not have firm boundaries, with similar models easily confused (Norman, 1985). Students sometimes fail to recognize their existence and do not always know how to effectively use them. Mental models are often used as a means of minimizing effort: "People will often do extra physical activities -- sometimes very time consuming and difficult -- in order to avoid a little bit of serious thinking." (Redish, 1994, p. 797).

According to Norman (1985), "Mental models are parsimonious: Often people do extra physical operations rather than the mental planning that would allow them to avoid those actions." (p. 8). This situation is evident when students rely on equations to solve qualitative problems.

Mental models are important for two reasons. First, they are part of a student's prior knowledge which influences what they attend to. Mental models are part of the student's existing conceptual frameworks\(^3\). Second, mental

\(^2\) According to diSessa, p-prims are considered to be the ultimate explanatory elements that begin with common sense observations. The initial formulation of the p-prims begin as disparate and isolated special cases. The idea of p-prims was first proposed by Goethe (1978).

\(^3\) Mental models can be thought of as a portion of the student's conceptual framework that pertains to a specific concept or domain. A conceptual framework may therefore contain multiple mental models.
models influence how students' qualitatively reason about new phenomena (Williams, Hollan, and Stevens, 1985). One view of teaching is to assist students in progressing from naive to novice to expert mental models; that is, to assist students in constructing personal mental models that are congruent with scientific models. Personal models are based on personal experience and are different from scientific models.

**Personal vs. Scientific Models and Theories**

Scientific theories are used to describe and summarize an organized collection of principles and assumptions that are used to explain phenomena. A scientific model is a simplified, symbolic representation of a system or process. Scientific theories and models represent the current views of experts in the science community. As discussed above, personal theories and models are constructed by the student to explain complicated but familiar phenomena based on personal experience. Personal theories and models are often intuitive beliefs that are fragmentary, internally inconsistent, and in conflict with accepted scientific theories and models.

It is difficult to change students' existing personal models which are often firmly held and incorporate misunderstandings about the phenomena. Empirical evidence will not always convince students that their current beliefs are inadequate. Students often attend to only those aspects of the experiment that supports their beliefs. Information is always interpreted on the basis of one's own beliefs: pre-existing conceptions, therefore, will influence what is attended to, what is remembered, and how it is interpreted. According to Duit (1991a, p. 71), "Students' conceptual frameworks guide observations" which in turn influences what is learned. The situation is made even more difficult when
students’ personal models are supported in their everyday lives, as in the case of electricity. Students often view electricity as consisting of current that is consumed: batteries run down and appliances are plugged into wall outlets with no apparent return route for the current.

Instruction is not enough: students’ confidence levels and trust in their “everyday” knowledge is often greater than in their “scientific” knowledge. Students will tend to use what they are more confident with. Rather than give up their personal constructs that explain phenomena in their lives, students will compartmentalize and protect their personal models. In other words, students often hold two separate sets of incompatible beliefs, one that explains experience in their everyday world, and one that explains what they see in the classroom. Students will often view the classroom examples as special circumstances. Students are able to memorize facts they learn in science class, but continue to apply their personal models outside the science classroom. This situation does not change with the age of the child: older students hold just as firmly to their personal models while using more sophisticated terminology (Glynn, Yeany, & Britton, 1991).

To promote changing personal models, teaching needs to address changing conceptual frameworks. Conceptual change teaching and learning addresses this issue.

**Conceptual Change Learning and Teaching**

**Conceptual Change View of Learning**

Learning is viewed as a type of conceptual change inquiry (see for example, Strike & Posner, 1985) that involves relating what one newly
encounters with what one already knows. To understand a new idea, that idea has to be placed within an existing conceptual framework, or a new conceptual framework needs to be constructed. Conceptual change has been described in a number of different ways by different researchers. Norman's theory of complex learning (1978) describes three processes: accretion, restructuring, and tuning.

Accretion, similar to conceptual development, represents the addition of new knowledge into existing knowledge. Conceptual restructuring occurs when existing knowledge is re-organized into more appropriate frameworks. The third process of learning is tuning, in which existing knowledge structures are refined and made more efficient. Although Norman (1978) attempts to explain learning of complex material and not conceptual change per se, his theory supports the idea of the existence of conceptual frameworks that he considers critical for learning complex information. Norman also points out the possible existence of different modes of learning including the importance of analogical reasoning.

Carey (1985) categorizes conceptual change into two categories: First, conceptual change can involve the assimilation of new concepts into an existing conceptual framework. There is little if any change in the original framework. This process is also termed weak restructuring. Weak restructuring involves a rearrangement of relationships among existing concepts. The concepts themselves are not changed, only their applicability. The second process involves the reorganization and elaboration of an existing conceptual framework to accommodate the new information. This process is termed accommodation or radical restructuring. Radical restructuring involves changes in the concepts.

Pines & West (1986a) described conceptual change in terms of three processes: conceptual development, conceptual resolution, and conceptual
exchange. Conceptual development is the acquisition of formal knowledge through the integration and differentiation of that knowledge into existing cognitive structures. Conceptual resolution, comparable to Norman's conceptual restructuring, occurs when students are forced to reconcile pre-existing ideas with conflicting situations. Conceptual exchange is the process of creating a new framework while abandoning one that was previously held to be true. Conceptual exchange is not the compartmentalization that can occur when students fail to abandon old ideas for new ones, preferring instead to keep both. Conceptual exchange, similar to radical restructuring, requires major shifts from one belief system to another.

Dykstra, Boyle, and Monarch (1992) propose three potential categories to describe conceptual change and use as a beginning of a taxonomy of conceptual change. These categories are: (a) differentiation where new concepts emerge from more general concepts (e.g., differentiating electric current and electrical energy out of the more general idea of electricity); (b) class extension where existing concepts once thought of as different are found to belong to a broader class (e.g., forces acting in static versus dynamic situations are still forces); and (c) reconceptualization where there is a significant change in the nature and relationship between concepts (e.g., caloric versus kinetic models of thermal energy).

Conceptual change theories are concerned with understanding the conditions that promote accommodation or radical restructuring, and the features of a student's alternative conceptual frameworks which influence the concepts selected within the process of conceptual change (Posner, Strike, Hewson, & Gertzog, 1982). Although there has been considerable investigation
of students' alternative frameworks, there is currently no well-articulated theory
that describes the process in which one set of concepts change to another set that
was incompatible with the first (Posner, Strike, Hewson, & Gertzog, 1982). In
addition, Smith (1991) argues that (1) studies contrasting students' naive
conceptions to scientific theories, (2) cognitive theories of conceptual
understanding and knowledge structures, and (3) models of conceptual change
are useful in characterizing what cognitive changes need to occur for learning to
take place, but are less helpful in characterizing how the process of conceptual
change can be promoted. According to Posner and his colleagues (Posner, et. al,
1982), the following conditions are necessary for accommodation to occur:

1. Dissatisfaction with existing conceptions. Failure of a student's
   conceptual framework to explain or predict adequately a new set of
   conditions will lead to cognitive conflict.

2. The new conception is understandable (intelligible). Use of analogies
   and metaphors can make new concepts more intelligible.

3. A new conception appears to be plausible. Use of analogies and
   metaphors can make new concepts more plausible.

4. A new concept appears to be more fruitful, useful, or provide more
   benefit or gain than the old conception.

Dykstra, et al. (1992) also propose that conceptual change is initiated by
disequilibrating students' prior conceptions. Disequilibration is similar to
concept dissatisfaction except more forceful. For instance, students are often
startled to observe that a simple piece of cardboard placed on top of a full
container of water will, when inverted, remain "attached" to the container.
Students find it hard to believe that the weight of the water does not force the
cardboard "lid" off. This startling effect is characteristic of disequilibrating activities. Concept dissatisfaction is more subtle in that the students' current beliefs do not explain or account for all their observable phenomena, and therefore, their ideas become less useful.

Accommodation is rarely a straight forward, linear process in which students have dissatisfaction with their existing ideas, find a new idea intelligible and plausible and therefore accept it as useful. Rather, accommodation, for the novice in particular, will be gradual, piecemeal, and circular. Students tend to visit, accept, reject, and revisit ideas before accommodation or radical restructuring of their knowledge base will occur. (This situation provides a good argument for a spiral curriculum in which ideas are revisited in different contexts and in greater depth.) Accommodation includes an additional difficulty: "Learning is not simply a matter of adding new knowledge, nor a matter or correcting incorrect information. The prior knowledge includes interpretive frameworks that the learner uses to make sense of the world and to communicate with other people. It is these interpretive frameworks that must change" (Smith, 1991, p. 44). Ultimately, how and when accommodation occurs depends on students' prior knowledge as well as a variety of other factors such as motivation.

However the process is described, researchers and educators agree that "... the process of change is a long and painstaking one. Students -- especially in the beginning -- are not willing to change their views of learning. First, the new view is much more demanding that the old one. Second, there is no immediate payoff in a school system that rewards learning outcomes that can be achieved more easily with the old techniques." (Duit, 1991a, p. 78).
Conceptual Change View of Teaching

A constructivist view of science instruction emphasizes the relational nature of science conceptions (Duit, 1991a). Studies in physics (e.g., Chi, Feltovich, & Glaser, 1981) comparing the knowledge bases and problem solving skills of novices and experts show that experts not only have more knowledge than novices, but the knowledge is better organized and more elaborate. The schemata of experts are based on physical principles whereas novices are based on physical objects and constructs. Experts’ schemata are organized hierarchically and based on more abstract principles. In addition, the experts’ knowledge base includes links between the abstract representational features of problems and the physical principles needed to solve the problems. Research compiled by Champagne, Gunstone, & Klopfer (1985) indicated that the pre-instructional declarative knowledge of beginning physics students concerning the causes of motion show that students have poorly differentiated concepts, use imprecise propositions describing relationships among concepts, and have explanatory schemata that are situation-specific.

Learning occurs through the development of relationships among concepts. Two important ways conceptual relations are formed are through the processes of organization and elaboration. According to Glynn and his colleagues (Glynn, Yeany, & Britton, 1991, p. 6), "Organizational processes are essential for building conceptual networks" and can be facilitated by such techniques as concept mapping. Elaborative processes have the students connect new information to information they already know.

One effective method for promoting elaborative relations is through the use of analogies, both student-generated and teacher-presented. Analogies also
provide a method of providing multiple representations of concepts that is effective in promoting conceptual change (Champagne & Bunce, 1991).

Analogies are particularly useful in promoting conceptual change in learning physics. The domain of physics offers considerable difficulties in developing conceptual understanding in naive students. This situation is due in part to the nature of physics, how it is typically taught, and the nature of changing conceptual frameworks, as discussed in the next section.

**Studying Conceptual Change in Physics Learning**

Studying conceptual change in physics learning is necessary because students come to class with firmly held and useful, alternative conceptions that differ from scientific ones. Traditional textbooks and methods typically do not address students' alternative frameworks and most students complete a physics course with their conceptual frameworks essentially unchanged. In other words, conceptual understanding, where students construct their own knowledge, does not occur even though students can successfully solve quantitative problems.

The problem arises when instruction simply presents students with concepts. This mode does not promote conceptual understanding because the information makes little sense to students given their existing frameworks. Conceptual understanding occurs when students construct meaning from their currently held beliefs. Therefore, an understanding of alternative conceptions as well as appropriate instructional strategies are necessary before conceptual understanding can be promoted. Instructional strategies that force students to challenge their beliefs include the learning cycle as proposed by Karplus (1980), microcomputer-based laboratory experiences developed by Thornton (1987),
disequilibration techniques as proposed by Minstrell (1989), and bridging analogies as proposed by Clement (1993). The next step is to provide experiences that promote reconstruction of conceptual frameworks, progressing students from their naïve stage towards a so-called expert stage congruent with current scientific beliefs.

The process of conceptual change from naïve to expert has not been adequately described. Although the differences between novice and expert understanding is well documented, Ledbetter (1993, p. 611) states “Few researchers have scrutinized the constructions that science students create.” In other words, what occurs as students progress from novice to expert is not well documented. Dykstra, Boyle, & Monarch (1992) propose that there are various kinds and degrees of conceptual change, and that it is necessary to explicitly represent students’ alternative conceptions at each stage of developing understanding in order to determine the appropriate instructional strategies. Conceptual change begins with an understanding of the students’ alternative frameworks, their naïve conceptions, that are demonstrated by their difficulties with concepts. The difficulties students have with electric circuits are a prime example.

**Electric Circuits: A Look at Student Difficulties**

The domain of electricity offers very serious difficulties for many students. According to Arons (1990), “Our picture of electric current, even in simple resistive circuits, is very abstract, subtle, and sophisticated.” (p. 177). The domain is comprised of many associative abstract concepts that are not available for direct sense perception. For example, students will typically try two incorrect
wiring plans when they are asked to light a flashlight bulb using a single wire and one battery (see Figure 1):

![Figure 1: Wiring Plans of Novice Students](image)

Heller and Finley (1992) point out that elementary and middle school teachers often hold imprecise and inconsistent beliefs about the relationships between current, electrical charges, and energy. The teachers they investigated shared a common core of strongly held beliefs that formed a coherent, but incorrect and contradictory model of sequential current flow. Their model held the battery as the source of the current, the wires as being "empty of current" (charge) until the current is actually flowing, and the amount of current as fixed and consumed. This study is consistent with research conducted on secondary students and college students (e.g., Osborne, 1981; Riley, Bee, & Mokwe, 1981; and Rhoneck, 1983). For example, McDermott and Van Zee (1984) found that even after completing a standard introductory physics course including the lab section on circuits, students continued to hold on to and use their previously held, personal beliefs.

Arons (1982) questioned students enrolled in a calculus-based physics course on the behavior of simple circuits. Although 65 percent of the students
could successfully answer questions that involved the application of equations and formulae, only 30 percent were able to qualitatively explain circuit behavior correctly. In this situation, students demonstrated that they were able to carry out algebraic manipulations of equations without true conceptual understanding of the phenomena. This inability to carry out phenomenological reasoning is characteristic of students who have not developed a conceptual understanding of the phenomena. (It should be noted that phenomenological reasoning is rarely required of students during instruction and therefore, students rarely have the opportunity to develop that skill.)

In one study (Cosgrove, Osborne, & Carr, 1984), investigators examined student understanding before and immediately after instruction, and one year later. Students were asked to explain current flow in a simple circuit consisting of a single bulb and one battery. Student responses were categorized into four situations (Figure 2, next page): (1) unipolar, originating from one terminal and totally consumed, situation A; (2) bipolar, originating from both terminals and totally consumed, situation B; (3) sequential flow with some current consumed, situation C; and (4) sequential flow with current conserved, situation D.
Prior to instruction, 86 percent of the students depicted model C as the correct situation. After employing instruction based on a learning cycle of familiarization-challenge-application, 86 percent of the students depicted model D as the correct situation. Although these results are good, after one year 40 percent of the students depicted a model based on C, and 47 percent depicted a model based on D. The authors concluded that the learning cycle was not sufficient for long term retention of the concepts, and suggested that analogies be used as part of the teaching strategies.

Research on student understanding of electricity concepts show that students hold common personal beliefs which can be classified into six domains based on the nature of the difficulty. These domains are:

1. Current: Students believe that current is consumed and that it is the same in all circuits regardless of the circuit's configuration. In addition, students
believe that the wires are “empty of current” (that is, charge) unless current is flowing.

2. **Potential Difference**: Students are unable to distinguish between current and potential difference and fail to recognize that an ideal battery maintains a constant potential difference between its terminals. Students also fail to distinguish between potential and potential difference (that is, they do not realize that bulb brightness depends on how the bulbs are connected in the circuit, not where they are connected).

3. **Resistance and Equivalent Resistance**: Students are unable to distinguish between equivalent resistance and individual resistance in a circuit and believe that total resistance always increases.

4. **Circuit Configurations**: Students fail to understand and apply the concept of a complete circuit; that is, the necessity of a loop. Students have difficulty in identifying series and parallel connections. The term “series” has the connotation of sequentiality instead of a specific type of connection. The term “parallel” is thought of in terms of its geometrical property and not its electrical property. Students also have a tendency to focus on individual elements instead of the entire configuration of the circuit and fail to distinguish between branches connected in parallel across a battery and connected parallel elsewhere. Students rarely understand or recognize a short circuit.

5. **Language Usage**: Students fail to distinguish among associated concepts (e.g., charge & current, current & voltage, energy & power) and tend to use terms interchangeably. To complicate the situation even more, many terms are borrowed from everyday language, with its original meaning still in use (e.g.,
although water current is closely analogous to electrical current, there are differences).

6. **Formal Representations**: Students fail to recognize that a circuit diagram represents the electrical elements and connections, but does not represent its physical or spatial relationships. Diagrams of electric circuits are considered to be conceptual intermediaries in physics, illustrating the relationships between the constituent components (Joshua & Dupin, 1984). A wire junction between two components, in a physicist's view, signifies two things: first, current can pass through the two devices (an example of current-reasoning), and second, the connected points are identical in that they have the same potential (an example of potential-reasoning). To the expert, the two diagrams in Figure 3 represent the same thing. However, the novice often believes that the two diagrams represent two different situations.

![Figure 3 - Two Equivalent Circuits](image)

Although students do make incidental mistakes, they also show patterns of conceptual difficulties based on ways of reasoning (Licht, 1991). Reasoning refers to the ability to qualitatively reason about a situation. Student reasoning about electric circuits is associated with the personal beliefs outlined above. Inaccurate or inappropriate reasoning patterns can be classified according to the
nature of the reasoning (Licht, 1991; Cohen, Eylon, and Ganiel, 1983; Cosgrove, Osborne, and Carr, 1984). Since reasoning depends on the concepts involved, the discussion here will overlap the previous discussion. Faulty qualitative reasoning includes:

1. **Local and Sequential Reasoning:** Students fail to recognize that changes in one part of the circuit will cause changes in other parts as well. With sequential reasoning, students believe that bulbs farther from the battery will be dimmer with brighter bulbs closer to the battery. In local reasoning, students tend to focus on one particular element, for example, a single light bulb, instead of the whole circuit. Local reasoning implies non-conservation of current. This reasoning pattern tends to be the most persistent and most common method.

2. **Source-Consumer Reasoning:** Students believe that the battery is the source of the current and current is consumed (which explains why batteries run down). Students believe that the greater the resistance, the more current is consumed.

3. **Current-Focused Reasoning:** Students focus on the current and explaining its behavior. Potential difference is viewed as a consequence of current and students fail to consider it when analyzing circuit behavior. For a given circuit, the fact that potential differences within that circuit must be constant is rarely recognized. Emphasis on current may result because current is more concrete and intuitive than potential difference (Cohen, Eylon, & Ganiel, 1983). The opposite of current-focused reasoning is potential-focused reasoning which is rarely spontaneously exhibited by novice learners.

4. **Mechanistic Reasoning:** Students tend to rely on equations and using technical or mechanical methods to explain circuit behavior. Students will
attempt to assign arbitrary numerical values to circuit elements in order to use familiar equations. Students can be quite capable of carrying out complicated algorithms such as using Kirchhoff’s rules, and yet not be able to qualitatively analyze simple circuits (Cohen, Eylou, & Daniel, 1983). It is also termed technical reasoning because the learner relies on technical knowledge rather than conceptual understanding.

In sum, student difficulties consistently occur with the concepts of circuit and circuit configurations, current and current behavior, resistance and equivalent resistance, potential and potential difference, and the role of the battery. Predominate (and inappropriate) reasoning patterns used by novice learners include local/sequential reasoning, source-consumer reasoning, current-focused reasoning, and mechanistic/technical reasoning.

**Traditional Approaches to Teaching Electric Circuits**

The domain of electricity and simple circuits consists of highly abstract concepts most of which cannot be perceived directly. Formulae and equations are typically used to formally define concepts.

The content is not the only difficulty: how it is presented can cause problems as well. Most physics texts approach the teaching of electric currents very didactically. In *Fundamentals of Physics* (Halliday & Resnick, 1988), the topic of electric current is sixth in a series of seven chapters dealing with electrical phenomena: students are first introduced to the idea of an electric charge, focusing on static electricity (“Like charges repel and unlike charges attract” p. 535). Students are told the difference between a conductor and an insulator, are given the formula for Coulomb’s Law (attractive and repulsive forces between charges), and are told that charge is quantized (“exists only in discrete packets”
and conserved ("the net charge of an isolated system of charges does not change" p. 545). Example problems deal with imaginary particles interacting in space.

The authoritative presentation of abstract and difficult-to-comprehend topics forces students to memorize at the expense of understanding. The text continues by discussing the electric field associated with the charge, Gauss' Law which is a relation between electric charge and the electric field, and electric potential (voltage) and capacitance (storing charges). The concepts not only increase in complexity, but are built upon. If you do not understand or comprehend electric charges and electric fields, then understanding electric potential and capacitance is extremely difficult. Comprehending current and circuit behavior becomes virtually impossible, considering the necessity of understanding electric potential.

Current is first presented as "charges in motion" (p. 640) and then as the formal definition of $dq = i \, dt$ or "the amount of charge $dq$ that passes through a hypothetical plane ... is proportional to the length of time $dt$ required for all the charge $dq$ to pass through that plane." (p. 641). After a variety of sample problems, students are then presented the definition of resistance ($R = V/I$). Moving to the next chapter, Electromotive Force and Circuits, students attempt to understand how it is all connected.

Overall, the text focuses on formal mathematical definitions, reinforced by abstract example problems involving manipulation of equations, and concepts presented in an authoritative, here's-what-you-need-to-know manner. It is not surprising that students who are capable of correctly solving problems using
formulae and algebraic manipulations of equations are not able to qualitatively explain the how’s and why’s of circuit behavior.

**Conceptual Change Approach to Teaching Electric Circuits**

To understand the concepts and phenomena underlying the domain of electricity and, more specifically, simple electric circuits, students need to explore in a qualitative fashion and be encouraged to reason about the phenomena without relying on equations and formulae that are often used as crutches. Arons (1982) maintains that students need to practice phenomenological reasoning in order to conceptually understand the phenomena. He goes on to state that “An area in which most students are very much in need of help with phenomenological (qualitative) reasoning is that of elementary resistive direct-current circuits.” (p.15).

Arons approach of utilizing simple materials, direct student interaction, and qualitative reasoning about the phenomena is advocated by a number of different researchers and educators. “Teaching about electric circuits needs to begin by exploring the behaviour (sic) of simple electric circuits in terms of directly observable variables, such as number of cells (batteries) and bulb brightness, rather than physics terms like energy and current.” (Licht, 1991, p. 273-4). The following approach (simplified here), considered to be an effective method for promoting conceptual understanding about electric circuits, was developed by Arons (1990) and refined by Shaffer and McDermott (1992):

Provide the student with one flashlight bulb, a piece of insulated wire with the ends bare, and one battery. Tell the student to light the bulb and sketch all configurations attempted. Group the attempts according to whether the bulb did or did not light. The student should be able to determine, with some guidance, four possible configurations that will
work and any number of those that did not work. Ask the student to describe in words what the successful arrangements have in common, and how they differ from the unsuccessful attempts.

From this interaction, the student should recognize the "two-endedness" of both the battery and the bulb and the necessity of forming a continuous loop. Some students may need more guidance or structure in reaching that objective. Arons advocates an instructional strategy of "idea first/name afterwards"\(^4\) and in this case, the term "circuit" would not be introduced until after students understand the key ideas: two-endedness and continuous loop.

The next step focuses on developing an understanding of what is meant by conductors versus non-conductors (or insulators). Introduce a variety of objects and have the students determine which objects will allow the bulb to light, and which don’t. After they have classified the objects accordingly, introduce the terms "conductor" and "non-conductor." Ask the students whether air is a conductor or non-conductor and explain what they are basing their answer on.

Students continue to explore circuit behavior by testing different circuit configurations: for example, location of bulb in circuit, bulb brightness at each location, uniform heating of wire when attached directly to the battery, immediate lighting of bulb regardless of placement or length of wires. Through guided explorations, students develop the concept of the electric current.

Once the student is able to conceptualize the basis of something flowing, continued guided exploration can lead to understanding of resistance, series and parallel connections, short circuits, and the role of the battery. Aron’s predominant instructional strategy continues to be guided exploration, which is consistent with scaffolding or learning-as-assisted-performance. In each case, the student has an increasingly more directive role in his or her learning.

\(^4\)As Richard Feynman said: "There’s a difference between knowing the name of something and knowing something."
As with most concepts, the deeper the student explores, the more complex the relationships become. Guided exploration cannot be the sole instructional strategy to develop conceptual understanding. Ultimately, the student must develop an accurate mental model that also corresponds with the current scientific explanation of the phenomena. It must be stressed that the model must be built by the student and not delivered by the teacher (Duit, 1984) and that learning must begin where the student is, with the students' existing conceptual frameworks. How the concepts are presented must make sense to the student. One way to reach students and challenge their current understanding is through the use of analogies.

The Importance of Analogies

It is important to distinguish between analogy, metaphor, model, and example. Although they share some characteristics, their use in teaching and learning can be quite different. An example is an instance of something: A Blue Jay is an example of a bird. A metaphor attempts to compare two things, normally not compared, without doing so explicitly and usually invoking an element of surprise or anomaly: A teacher is like a captain of her ship. If taken literally, the comparison is absurd. Analogies also attempt to compare two things, but in this case, the comparison is usually more direct and explicit, focusing on structures: The heart is like a pump. In this case, the heart functions like a pump in that it moves liquid. A model can be considered a familiar analogy with a specific, accepted explanatory purpose: The planetary model of the atom. Often model and analogy are used interchangeably.

Analogies are important in science education for two reasons. First, working from a constructivist perspective, analogies provide a means of relating
unfamiliar concepts with familiar ones allowing the learner to construct meaning. Second, analogies are also used in scientific reasoning, specifically, in the development of theories and models of explanation. If used properly, analogies provide students the opportunity to observe and participate in the same methods of inquiry that scientists use to develop their understanding. Analogies can, therefore, help students develop an understanding of the nature of science and science inquiry.

Analogies provide a mechanism allowing students to use their existing knowledge structures to make sense out of new information by making that information more intelligible and plausible (Posner, et al., 1982). Relating new knowledge to an existing conceptual framework within the same domain is not effective in promoting radical restructuring; for instance, comparing a bird's eye to a human eye. However, using analogies or metaphors to relate knowledge between domains is an effective way; for example, comparing a camera to a human eye. Vosniadou & Brewer (1987, p. 61-62) state that "Analogies can play different roles in restructuring. They can facilitate both the spontaneous restructuring of new schema, and the explicit teaching of a new structure..." -- two forms of radical restructuring. Analogies help students make their existing knowledge more explicit by assisting them to see what they do and do not understand. As explained by Duit (1991b),

The following two basic ideas of [the constructivist] view are of central importance: (1) learning is an active construction process; and (2) learning is possible only on the basis of previously acquired knowledge. [...] Learning, therefore, fundamentally has to do with constructing similarities between new and the already known. It is precisely this aspect that emphasizes the significance of analogies in a constructivist learning approach.

(p. 652)
Analogy is indeed an indispensable and inevitable tool for scientific progress ... Whether or not we talk of discovery or invention, analogy is inevitable in human thought, because we come to new things in science with what equipment we have, which is how we have learned to think, and above all how we have learned to think about the relatedness of things. We cannot, coming into something new, deal with it except on the basis of the familiar and the old-fashioned. The conservation of scientific enquiry is not an arbitrary thing; it is the freight with which we operate; it is the only equipment we have. We cannot be surprised or astonished at something unless we have a view of how it ought to be; and that view is almost certainly an analogy.

(quoted in Glynn, 1991, p. 220)

Oppenheimer makes two important points: First, analogy use is a legitimate form of scientific inquiry, and second, what you already know or believe is as important as what you are trying to find out. Analogy use not only provides students with a clearer picture of the process of science and science inquiry, but it provides them with another tool for constructing understanding in science.
Models of analogy use

There are currently four dominate models, or major theoretical frameworks, for analogy use in teaching and learning science. These models are structure-mapping theory, general model of analogy teaching, teaching-with-analogies model, and bridging analogy model. Each model will be examined in detail below.

Structure-Mapping Theory proposed by Gentner (1983) is mainly derived from a psychological perspective with supporting research from science education. According to Gentner (1983, p. 155), “A theory of analogy must describe how the meaning of an analogy is derived from the meanings in its parts.” Knowledge is assumed to consist of “prepositional networks of nodes and predicates... the nodes represent concepts treated as whole; the predicates applied to the nodes express propositions about the concepts” (1983, p. 157). The emphasis is placed on the structures, not surface features, of the concept to be learned (target) and its analog. That is, the relations between the objects are mapped from the analog to the target, not the surface attributes. The theory specifies the “systematicity principle” which states that an effective analogy should map systems of relations (interconnected relationships) and not merely single aspects.

The theory distinguishes between literal similarity, analogy, and relational abstraction as a continuum of comparison types. A literal similarity maps mainly object-attributes, with possibly some relational predicates. Most if not all would be mapped. An example of a literal similarity is comparing the X12 star system in the Andromeda galaxy to our own solar system. An analogy maps mainly relations, with few object-attributes, and not all items can be mapped.
example, comparing the hydrogen atom to our solar system would be considered an analogy because the focus is on the relationship within each object. An abstraction involves comparing two abstract objects. The example Gentner gives is “The atom is a central force system” (p.160). Figure 4 illustrates the overlap between the three types of comparison.

![Figure 4 - Types of Comparisons](image)

As pointed out by Duit (1991b), the structure mapping theory is useful for two reasons: First, the theory assists in distinguishing between analogies with low vs. high inferential power, and second, the analogy should map substantial relational features, or systems of relations, and not just single aspects. There are concerns with the model. First, it assumes that “adults are predisposed to map constrained relational systems, rather than nonsystem (isolated) relations or literal surface features.” (Zook and DiVesta, 1991, p. 246). Accordingly, learners would have to be aware of what constitutes a mappable relational system. Novice or young learners may require special guidance in analogy use to prevent misconceptions from forming, as Zook and DiVesta (1991) discovered. In addition, salient surface features do influence the spontaneous selection of an analog (Holyoak & Koh, 1987).
The General Model of Analogy Teaching (GMAT) (Zeitoun, 1984) is based on schema theory presented by Rumelhart & Norman (1981). Zeitoun defines an analogy as an “interpretive bridge between the unfamiliar topic and the knowledge which students have” (p. 107). According to GMAT, effective analogies have the following characteristics, using the analogy that the human eye is like a camera:

1. The topic of the analog is unfamiliar; the structure and function of the eye may be unfamiliar.

2. The analog is familiar and easily visualisable material; the camera is generally familiar and easy to visualize. (Concrete models are readily available.)

3. There are shared attributes between the analog and the topic; both the eye and the camera have a lens, an iris (aperture), and a means of recording light (the retina and the film).

4. There are irrelevant or mismatching attributes between the analog and the topic. In the case of the eye, the retina does not store the image as the film does.

The model specifies nine steps or stages for analogies teaching, as shown by Figure 5, next page.
Student characteristics (#1) that may influence the effectiveness of the analogy include such things as familiarity with the analog, analogical reasoning ability, Piagetian cognitive levels, visual imagery ability, and level of cognitive complexity (i.e., novice vs. expert knowledge structures). Instructional variables (#'s 5, 6, 7) include complexity of the analog, how concrete the analog is, availability of multiple analogies, format of presenting the analogy, teaching strategy used (teacher-presented vs. student-generated), and type of media used (written, verbal, visual, etc.).
Zeitoun concludes by discussing the limitations of analogy use. An analogy will have little or no effect if the analog is unfamiliar to the student, if the student possesses enough background knowledge about the topic (analog is unnecessary), the student lacks certain abilities such as analogical reasoning, visual imagery, etc., or the number of analogous attributes is limited and the number of irrelevant ones are superfluous. Other problems can arise if the analogy is taken literally, thereby promoting misconceptions. Finally, the student can be misled into thinking the analogy presents all necessary information about the topic, when in fact, analogies tend to convey limited information.

The theory, according to Duit (1991b), lacks a strong theoretical basis, is overly pragmatic, and important aspects of analogy use are not fully accounted for. For instance, the importance of prior knowledge is only mentioned in passing.

The Bridging-Analogies Model (Clement, 1987; Brown & Clement, 1989; Brown, 1992; Clement, 1993) attempts to solve several difficulties with analogy use. First, students fail to understand the analogy due to lack of prior knowledge or experience. Second, students do not make the intended comparisons and therefore fail to develop the understanding hoped for. Third, the analogies are not powerful enough to force the students to abandon their previously and strongly held conceptions. Clement’s approach takes a deliberate constructivistic approach -- student-oriented participation involving a negotiation of views that employ aspects of Socratic dialogue.

This model works by deliberately beginning with an “anchor” analogy to prompt a correct intuition from which to build conceptual understanding. A
series of additional analogs are used to bridge the gap between the anchor and the final concept. An example of the bridging analogy approach uses a starting anchor of a spring on a table to allow students to investigate the concept of a table "pushing up" on a book resting on it. Most students do not believe that an inanimate and unmoving object, such as a table, can apply a force on another object. The students press on the spring and feel the resultant force of the spring acting on their finger. The next analogies involve a book lying on the spring, followed by the book lying on a thin board, followed by the book lying on foam, and concluding with the target problem -- the book on the table. A discussion focusing at the microscopic level of the book/table is used to tie the spring analogy back to the target concept. Figure 6 illustrates the approach.

![Diagram of Bridging Analogy](image)

**Figure 6 - Example of a Bridging Analogy**

Acknowledged problems with the model include the limited availability of good anchors and bridging analogies, and student views often differ from scientific views.

The Teaching-with-Analogy Model (TWA) was developed at the University of Georgia (Glynn 1989, 1991 & Glynn et al., 1989) and takes a
constructivist approach. The model is based on theoretical considerations concerning analogy use, empirical studies on analogical reasoning, and an analytical study about analogy use in physics textbooks. According to Glynn (1991), an analogy is "a process of identifying similarities between different concepts." (p. 223). Meaningful learning occurs when associations and relationships can be established among experiences, concepts, and frameworks. Analogies work by making explicit a set of associative relationships between something that is familiar and easily understood and something that is unfamiliar. According to this model, analogies serve two functions: explanation and creativity. Analogies serve as explanations when they place unfamiliar concepts in familiar terms, and serve a creative function when they stimulate solutions to existing problems, identify new problems, or generate new hypotheses.

A key component of this model is the idea of a superordinate concept, which is applied to both the analog and the topic. According to Glynn (1991), "The identification and naming of the superordinate concept can suggest other analogies; it also can stimulate students to generalize what they have learned and apply their learning to other contexts." (p. 225). Figure 7, next page, represents the TWA model for an analogy and the role of the superordinate concept.
The model specifies six steps or operations to perform when teaching with analogies. These operations are:

1. Introduction to target concept,
2. Recall analog concept,
3. Identify similar features,
4. Map similar features,
5. Draw conclusions, and
6. Indicate where the analogy breaks down.

The model is intended only as a guide to teaching with analogies and the developers recognize the need for empirical studies to validate this model. In particular, "Ethnographic studies of teacher-student-textbook interactions that involve analogies would be particularly appropriate." (Glynn, 1991, p. 238).

In the next section, analogies in physics will be explored with particular attention to examples in the teaching of electricity.
Analogies associated with the teaching of electric circuits

Designing effective instructional methods and materials is critical with abstract subject domains such as current electricity where students have numerous and deep-seated alternative conceptions. Analogies, therefore, hold potential promise as an instructional method. Analogies are particularly useful in subject domains where the concepts are abstract and where students have difficulty in visualizing the concepts and relationships among the concepts. Physics has been described as a subject area where everyday language takes on highly specialized meaning, and whose concepts tend to be not only abstract but often contradictory to everyday experience. Such is the case with the study of electricity. There are three widely used analogies for electric circuits: The hydraulics or water flow analogy, the teeming crowd analogy, and the train or mechanical analogy.

In the hydraulics analogy, the analog is a plumbing system consisting of a reservoir of water and a circulating pump (the battery), water pipes (wires), a narrow constriction in a pipe (resistor), and flowing water (electric current). The analogy is meant to convey a set of relationships readily visualizable in the analog transferable to the domain of electricity. Figure 8, next page, illustrates a simple electric circuit consisting of a battery connected to a bulb using wire and its hydraulics analogy.
The water reservoir, with its outlet at its base, provides a certain amount of pressure proportional to the height of the water. The amount of water flowing past a certain point in a given amount of time is the system’s rate of flow. The rate of flow is proportional to the difference in pressure through a particular section. The greater the height of water, the greater the flow rate, assuming all else is equal. A constriction in the pipe will lead to a drop in pressure, and a reduction in the flow rate throughout the system. The greater the constriction, the less the flow rate through that system.

In an electric circuit, electrons flow because of a voltage difference supplied by the battery, just like the water reservoir supplied a pressure difference in the system resulting in flowing water. The current is the number of electrons passing a given point per second, similar to the rate of water flow. A resistance in the circuit, such as a light bulb or resistor, reduces the current flowing through that particular circuit -- not just the resistor -- just like the pipe constriction slowed down the rate of flow of the water throughout the system. Table 1, next page, illustrates the correspondences between the analog and the target.
Table 1 - Correspondences of Hydraulics Analogy
For Electric Circuits.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Base (Hydraulic System)</th>
<th>Target (Electric Circuit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object-attributes</td>
<td>Pipe</td>
<td>Wire</td>
</tr>
<tr>
<td></td>
<td>Reservoir</td>
<td>Battery</td>
</tr>
<tr>
<td></td>
<td>Constricted Pipe</td>
<td>Resistor</td>
</tr>
<tr>
<td>Property-Attributes</td>
<td>Pressure of water</td>
<td>Voltage</td>
</tr>
<tr>
<td></td>
<td>Narrowness of Pipe</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Flow rate of water</td>
<td>Current</td>
</tr>
<tr>
<td>Relational Attributes</td>
<td>Increase pressure, increase flow</td>
<td>Increase voltage, increase current.</td>
</tr>
<tr>
<td></td>
<td>Increase constriction, decrease flow rate</td>
<td>Increase resistance, decrease current.</td>
</tr>
</tbody>
</table>

The analogy may help naive students understand the simpler proportions of "more force, more flow" and "more drag, less flow" that constitute Ohm's Law (\(V = IR\)). This analogy can also help establish the concept of conservation of current. In a river, water is conserved in that the same flow rate (or amount of water per unit time) remains constant as the river changes from a wide, slow moving body of water to a narrow, fast moving body, such as a water fall. Otherwise, water would build up (river height would change), which does not happen.

The hydraulics analogy explains combinations of batteries easily, but does not adequately represent combinations of resistors. Two reservoirs of water, one on top of the other, will result in twice the flow of water because the height has doubled (series circuit). However, if two reservoirs are placed side by side (parallel circuit), the flow rate does not change because the height of water does not change. Constrictions in the pipe are viewed as impediments to flow (more
drag, less flow); therefore, regardless of whether two resistors are placed in parallel or in series, the water is subjected to two obstacles rather than one, resulting in less flow.

The second analogy is the **teeming-crowd analogy** developed by Gentner & Gentner (1983). Also called the moving-crowd analogy, people are running around a race track with gates corresponding to resistors. The battery is not easily represented in this analogy, although some have suggested a blaring loud speaker as the impetus of movement. Combinations of resistors are more readily understood. The resistors are represented by gates through which people must pass, one at a time. If there are two gates, one right after the other (series), everybody must pass through both gates, resulting in a slow down. If, however, the gates are side by side (parallel), then the people have a choice of which gate to go through with each gate allowing the same flow. Therefore, the overall flow rate should be twice the rate for a single gate. That is, resistors in series will lead to less current than a single resistor, and resistors in parallel will lead to more current than a single resistor.

A third analogy for electric circuits is the **train analogy** (Dupin and Johnsua, 1985). The train analogy consists of a continuous train moving around a circuit, propelled by men, in the station, pushing it with a constant force (See Figure 9, next page).
Table 2 illustrates the correspondences between the analogy and the base domain.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Base (Train System)</th>
<th>Target (Electric Circuit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object-attributes</td>
<td>Train track</td>
<td>Wire</td>
</tr>
<tr>
<td></td>
<td>Train station &amp; workers</td>
<td>Battery</td>
</tr>
<tr>
<td></td>
<td>Constricted track</td>
<td>Resistor</td>
</tr>
<tr>
<td>Property-Attributes</td>
<td>Pushing workers</td>
<td>Voltage</td>
</tr>
<tr>
<td></td>
<td>Constriction of track</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Flow rate of cars</td>
<td>Current</td>
</tr>
<tr>
<td>Relational Attributes</td>
<td>Constant Force (p=Fv)</td>
<td>emf</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>Power (P=EI)</td>
</tr>
</tbody>
</table>

According to Joshua and Dupin (1993), this analogy has three advantages:
First, the analogy helps students to distinguish between the motion of matter and energy consumption which helps to establish the concept of conservation of current. Second, the analogy promotes the ideas of a constant current throughout a series circuit and the global effects of changes. Third, the analogy allows students to explore the concepts of emf, current, and resistance. This analogy does have problems: emf is treated only superficially, an open circuit is not explained, and no distinction is made between current flow and current
speed. Although this analogy was not used in the computer tutorial, it was used to develop an analogy for the battery, the conveyor-belt analogy.

An analogy for the internal functioning of the battery is the **conveyor belt analogy**. This analogy consists of a conveyor belt inside the battery, propelled by men, which causes the charges to separate (See Figure 10).

![Figure 10: Conveyor Belt Analogy for a (single cell) Battery](image)

Table 3 illustrates the correspondences between the analogy and the base domain.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Base (Conveyor System)</th>
<th>Target (Electric Battery)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object-attributes</td>
<td>Men on conveyor belt</td>
<td>Chemical reaction</td>
</tr>
<tr>
<td>Property-Attributes</td>
<td>Charge separation by mechanical means. Walking workers</td>
<td>Charge separation by chemical means. Voltage</td>
</tr>
<tr>
<td>Relational Attributes</td>
<td>Men tire and quit, no current Constant motion</td>
<td>Chemical reaction ceases, no current emf</td>
</tr>
</tbody>
</table>

Analogies are useful in that they provide more easily visualized situations that, if approached correctly, would be more familiar to the students. However,
all analogies break down at some point. The hydraulics analogy is not as effective in illustrating the relationships associated with combinations of resistors as compared to the teeming-crowd analogy. Following the advice of other researchers (e.g., Spiro, et al, 1989), using multiple analogies would minimize the number of misconceptions students would make. For this reason, the computer tutorial will incorporate the analogies of water flow, teeming-crowd, and the conveyor-belt.

A Constructivistic Instructional Program for Electric Circuits

According to the research, an appropriate instructional program to promote conceptual understanding would: (a) begin with students' existing alternative frameworks; (b) engage students in situations where they are forced to challenge their existing frameworks through, for example, disequilibrating experiences; (c) build from students' existing frameworks by making the new information sensible through such strategies as analogies; and (d) involve the students in a series of hands-on and minds-on experiences that allow them to construct and reconstruct progressively more sophisticated mental models.

For the teaching of electric circuits, such an instructional program would closely follow the program developed by Arons (1990) and Shaffer and McDermott (1992) as discussed previously. The instruction would make use of appropriate analogies and strategies from the Teaching-with-Analogies model and the Bridging-analogies model. In addition, the instruction would provide students with simple materials such as batteries, flashlight bulbs, and wire, to test and explore their ideas, concepts, and models. The instruction would also
take advantage of computers and simulations which provide an interactive, graphic media to present and explore analogies and associated concepts.

According to Krajcik, Simmons, and Lunetta (1988, p. 148), "Interactive graphics and dialogue are two features enabling computer software to become powerful tools in science teaching. Appropriate simulations and tutorials can help students learn about the natural world by having them visualize and interact with underlying scientific models that are not readily inferred from first-hand observations." Simulations that allow for the manipulation of phenomena that are not directly observable may facilitate learning of highly abstract concepts that would be difficult to achieve with conventional instructional materials. Reif (1987) argues that computers have the unique capability of providing powerful graphical representations of phenomena, can easily store and re-display student work allowing for re-examination, and provide an independent learning environment that offers guidance to the student. Computer-facilitated learning may increase conceptual understanding for other reasons as well: learning increases when students are provided with immediate and informative feedback and motivation can increase when students are able to select the level of difficulty and challenge that are appropriate for their background and ability.

Computers can not only facilitate learning, but if used properly, computers can also aid in research specifically on how conceptual understanding develops. McDermott (1990) describes how instructional software can be used to identify and analyze conceptual difficulties when used as an investigatory tool by providing an environment that allows the researcher to closely examine specific learning situations. Flick (1990) described his use of a computer program to capture keyboard sequences to investigate how students solve force and
motion problems. Zietsman and Hewson (1986) used computer simulations in conjunction with conceptual change strategies to investigate student understanding of velocity. Krajcik, Simmons, & Lunetta (1988) used a dynamic research strategy involving structured observations of students interacting with concepts presented via instructional software. Using this strategy, they investigated how students (a) develop concepts; (b) interact with instructional software; and (c) solve problems.

Investigating Conceptual Change in Physics Learning

A central premise for this study is the belief that qualitative understanding is necessary for students to be able to apply concepts and principles in real-world situations. Qualitative understanding results from the active construction of knowledge by the student, which in turn involves the reconstruction and construction of mental models.

Traditional physics instruction and assessment of learning usually involves testing students' performance on solving quantitative problems. Most educational research in physics uses the same approach: quantitative pre- and post-test measures as an indication of students' gain in conceptual understanding. However, current research has found that students' ability to solve problems does not measure their degree, if any, of conceptual understanding. Skill at quantitative techniques does not assure a qualitative understanding. Similarly, quantitative measures of students' performance prior to and after a research intervention does not provide information on the constructions and reconstructions that students make as they attempt to understand new concepts.
A qualitative research methodology that is congruent with the constructivist, conceptual-change basis of learning is needed (see, for example, Fischer & Auflshnaiter, 1993). Qualitative methods allow researchers to collect descriptive data that can be used to interpret student behavior to make inferences about their conceptual frameworks. Naturalistic research and phenomenographic research are two approaches that share a constructivist philosophy.

Naturalistic Research

Naturalistic research attempts to create a possible reality dependent on the context and formed by interrelationships of the subjects, environment, and researcher. Naturalistic inquiry uses predominately qualitative methods to provide rich, descriptive data. The research design often emerges from the research itself: the specific procedures are developed as part of the inquiry and in response to the conditions of the setting (Erlandson, et al., 1993).

Naturalistic inquiry cannot rely on traditional assessments of internal and external validity; rather, the naturalistic researcher is concerned building “trustworthiness” through establishing the following (Erlandson, et al., 1993). Trustworthiness is achieved through using a variety of different sources (triangulation); providing detailed, rich, and precise descriptions; documenting the process of the inquiry; and by seeking disconfirming or contrary evidence.

Phenomenographic Research

The phenomenographic approach to research is concerned with describing the ways students conceptualize, perceive, and understand the world (Johansson, Marton, & Lennart, 1985). This type of research seeks to articulate a student’s way of knowing from the perspective of the student - not the educator or scientist.
Previous phenomenographic research indicates that phenomena are understood in a limited number of qualitatively different ways. In other words, conceptions can be thought of as "categories of interpretation" (Johansson, Marton, & Lennart, 1985, p. 236). As a consequence, conceptions can be placed in "categories of descriptions" based on their similarities and differences. The ways in which students understand a concept guides the development of these categories. According to Walsh and his colleagues (1993), categories are derived from the data rather than attempting to fit data into predetermined categories.

**Model of Concept Application and Conceptual Maps**

These categories of descriptions are similar to the conceptual maps representing students' frameworks, as described by Dykstra, Boyle, and Monarch (1992). They propose a "Model of Conceptual Application" and the use of conceptual maps as a means of inferring students' personal conceptual frameworks. When referring to conceptual maps, Dykstra, Boyle, & Monarch (1992) are referring to those created by the researcher and not those used as an instructional strategy by the teacher and created by the student. The conceptual maps "represent, in an explicit and pragmatic way, concepts, terms, features, and their interrelationships that comprise students' knowledge, and which are obtained from verbal descriptions ... " (p. 617). In addition, successive conceptual maps can represent the changes students go through as they progress from naive towards expert understanding.

The conceptual application model provides a methodological framework for identifying students' conceptual frameworks. It is based on the hypothesis that specific student behaviors arise when conceptions are applied to specific problem situations. By studying how students interact in a variety of problem
situations, inferences can be made about their conceptual frameworks. Figure 11 illustrates this model.

![Figure 11 - Model of Conceptual Application](image)

Verbal data is used to construct conceptual maps that allow researchers to monitor conceptual change as students progress from their naive mental models to more sophisticated mental models.

The Model of Conceptual Application provides a methodology for identifying conceptions. According to the researchers, "the meanings of words students use to describe various situations and to explain their problem-solving actions must be organized into a representation which would enable us to determine how their conceptions are related to the categories they use to classify what they know about the world." (Dykstra, Boyle, & Monarch, 1992, p. 627). The representation they refer to is created by the researcher and is considered to be a "rational reconstruction of [the student's] conceptual knowledge." (Dykstra, Boyle, & Monarch, 1992, p. 627). The categories include objects, attributes, and situations which can have subcategories of states and processes. Relations are represented by explicit links between categories.
These categories are similar to the categories of description described previously. However, Dykstra and his colleagues go further by developing the categories into networked representations of the knowledge states of students: the so-called conceptual maps. According to Dykstra et. al (1992, p. 628), "Each conceptual map represents a particular state of knowledge and the transition from one map to another represents conceptual change." These conceptual maps provide a means of representing the processes of assimilation and accommodation. Assimilation is represented when new cases are created under existing categories. Accommodation is illustrated through the changes in a sequence of two or more conceptual maps.
Chapter 3

METHODOLOGY

Five pairs of students were followed as they worked through an instructional program that incorporated a computer tutorial with hands-on activities, aimed at developing conceptual understanding of simple DC circuits. The study employed a naturalistic research design that incorporated structured observations and utilized think-aloud protocols. The purpose of this study was to analyze the conceptual change and reasoning patterns of one pair of students as they progressed from naive towards more scientific models of electric circuits.

The study incorporated a series of preliminary trials that guided the development of the computer tutorial, the instructional program, and refined the research methodology to facilitate collection of verbal data. During the preliminary trials, student-student and student-tutorial interactions were examined to determine better ways of encouraging students to verbalize what they were thinking and articulate their models as they changed.

Design:

A dynamic research strategy was employed in order to explore how students utilized concepts and developed understanding when involved in an inquiry-based instructional program involving simple DC circuits. The program included a computer tutorial and manipulation of simple materials (e.g., wires, batteries, and flashlight bulbs). The instructional sequence was patterned after the program developed by Shaffer and McDermott (1992), involving inquiry-based activities and utilizing simple materials.
Structured observations were used to generate verbal protocol from videotape data and transcribed analysis of students' commentaries. Verbal protocol analysis (Ericsson and Simon, 1993) provided data for the development of conceptual maps (Dykstra, Boyle, and Monarch, 1992) from which students' conceptual frameworks and mental models were inferred.

The study also included pre-instructional and post-instructional assessment of students' conceptual understanding. These pre- and post-assessments aided in determining the characteristics of the students' mental models of simple DC circuits before and after participation in the instructional program. The pre-assessment also aided in the development of the instructional program and computer tutorial. The post-assessment was administered two days to one week after completion of the instructional program. Although an aim of this study was to document the conceptual changes that occurred during participation in an instructional program and the interim models that were developed, a post-assessment was necessary to describe the student's final, overall model of electric circuits and the extent of change from their initial naive model to their final model.

The computer tutorial employed multiple analogies and directive questioning to challenge and promote the development of conceptual understanding. The analogies selected were the hydraulics analogy, the teeming-crowd analogy, and the conveyor-belt analogy. The hydraulics and teeming-crowd analogies have research bases for teaching current flow and resistance of electric circuits. The conveyor-belt analogy for the battery was developed by the researcher and based on the train analogy used in the teaching of energy transfer and the role of the battery in electric circuits. The use of analogies in the
instructional sequence was guided by the Teaching-with-Analogy model proposed by Glynn (1991).

Subjects

Twenty-four undergraduate students enrolled in an algebra-based general physics course took the pre-instructional assessment. Ten students volunteered for the study and signed informed consent forms to participate (see Appendix A). Of the ten volunteers, one student did not take the pre-instructional assessment. The 10 students worked in pairs. Three pairs of students participated in the preliminary trials. The remaining two pairs of students completed the tested and revised instructional program. Only one pair, Don and Heather, was analyzed for this study. Table 4 shows the characteristics of the subjects who volunteered for the study. Bold lines delineate the pairs of students that worked together.

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>Major</th>
<th>GPA</th>
<th>Reason for taking course</th>
<th>First physics course?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heather</td>
<td>Senior</td>
<td>Sprts Med</td>
<td>3.8</td>
<td>Required for major</td>
<td>Yes</td>
</tr>
<tr>
<td>Don</td>
<td>Senior</td>
<td>not known</td>
<td>3.7</td>
<td>Elective</td>
<td>Yes</td>
</tr>
<tr>
<td>David</td>
<td>Senior</td>
<td>Geology</td>
<td>2.1</td>
<td>Required for major</td>
<td>HS, grade C</td>
</tr>
<tr>
<td>Henry</td>
<td>Junior</td>
<td>Phys. Sci</td>
<td>3.8</td>
<td>Required for major</td>
<td>Yes</td>
</tr>
<tr>
<td>Bettina</td>
<td>Junior</td>
<td>Biology</td>
<td>3.6</td>
<td>Elective</td>
<td>Yes</td>
</tr>
<tr>
<td>Steve</td>
<td>Senior</td>
<td>Phys. Sci</td>
<td>3.6</td>
<td>Elective</td>
<td>HS, grade C</td>
</tr>
<tr>
<td>Kim</td>
<td>Junior</td>
<td>Sprts Med</td>
<td>3.6</td>
<td>Required for major</td>
<td>Yes</td>
</tr>
<tr>
<td>Jen</td>
<td>Senior</td>
<td>Sprts Med</td>
<td>2.8</td>
<td>Required</td>
<td>Yes</td>
</tr>
<tr>
<td>Amy</td>
<td>Junior</td>
<td>Biology</td>
<td>3.4</td>
<td>Required for med schl</td>
<td>Yes</td>
</tr>
<tr>
<td>Rebecca</td>
<td>Junior</td>
<td>Biology</td>
<td>4.0</td>
<td>Elective</td>
<td>HS, grade A</td>
</tr>
</tbody>
</table>


Tutorial Development and Preliminary Trials

Results of the pre-instructional testing along with published research on conceptual change teaching of electricity guided the development of the five-session computer tutorial and instructional program. All five pairs of students completed each of the five sessions and took the post-test. Two of the five pairs of subjects completed each of the sessions after the sessions were refined based on the information collected from the other subjects. Don and Heather completed each session after the sessions were revised twice. Steve and Bettina completed all sessions, except sessions two and four, after the sessions were revised twice: Sessions two and four were revised only once. Table 5 indicates the time line showing tutorial development and when the subjects completed each of the sessions.

Table 5 - Tutorial Development Timeline

<table>
<thead>
<tr>
<th>Tutorial Session</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>D</td>
<td>C</td>
<td>B</td>
<td>E</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td>D</td>
<td>E</td>
<td>C</td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td>C</td>
<td>B</td>
<td>E</td>
<td>D</td>
<td>A</td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td>C</td>
<td>B</td>
<td>A</td>
<td></td>
<td>D</td>
</tr>
</tbody>
</table>

A - Don and Heather  
B - Steve and Bettina  
C - David and Henry  
D - Kim and Jen  
E - Becky and Amy

   Preliminary Tutorial  
First Revision  
Second Revision
The Instructional Program

Subjects progressed through a series of activities designed to promote the development and reconstruction of mental models. The lesson framework was similar to the learning cycle of exploration-invention-application developed by Karplus (1980). The computer presented questions and "student" interpretations to challenge the subjects' models of understanding and analogies to promote learning. The hands-on materials provided the subjects the opportunity to test ideas and explore situations. The instructional program targeted the following documented student difficulties:

(a) the concept of circuit including opened versus closed, conductors and insulators, and circuit diagrams;
(b) the behavior and nature of current including current dependency on circuit configuration, differences between series and parallel circuits, and conservation of current;
(c) resistance and equivalent resistance and the differences between resistances in series and in parallel; and
(d) potential energy, potential difference, voltage, and the role of the battery.

Setting

Data collection occurred in the researcher's office. Only those students participating in the instructional program and the researcher were present during data collection. A pair of students worked at a Macintosh IIvx computer with its video output connected to a videocassette recorder. A video camcorder and audio cassette tape recorder with individual microphone pickup recorded the students' verbalizations. Students were specifically instructed to speak aloud...
during the program, to talk and ask questions to each other, and to verbalize all thoughts no matter how inconsequential they seemed. Students were instructed on the basic operations of the tutorial prior to starting the first session. Students were encouraged to use paper and pencil to work through and record additional thoughts and ideas. The hands-on materials were located on a separate table within easy reach of the students and in view of the video camcorder. The set up is illustrated in Figure 12.

![Diagram of Data Collection Layout](image)

**Figure 12 - Data Collection Layout (Top View)**

**Instruments**

Pre-instructional and post-instructional assessments (See appendix B) provided an indication of the subjects' mental models and levels of conceptual understanding before and after instruction. Both tests involved subjects in qualitative analysis of circuits using paper and pencil tests. No actual circuits were available. The pre-instructional assessment also queried academic background and reasoning for taking physics.
Researchers Role

The role of the researcher is best described as participant-observer. The majority of the time, the researcher simply observed the interactions of the subjects and recorded pertinent information. Some of the time, the researcher intervened. Intervention was limited to helping the subjects understand new material as it was being presented, reviewing information previously presented, or asking the subjects to clarify or restate information in order to better understand the situation. The researcher did not present or use information, for example, specific terminology, until after the subjects had an opportunity to investigate and develop their own understanding. The interventions can be classified as follows:

1) To clarify a question, statement, or set of instructions presented by the tutorial but not clearly understood by the subjects;

2) To supplement the directions and/or information presented by the tutorial;

3) To ask subjects to restate and clarify their responses to a problem, question, or other situation; and

4) To probe subjects' understanding at a deeper level than what the subjects were presenting.

Data Sources and Collection Procedures

Data was collected from:

1. Videotapes of the five tutorial sessions.

2. Transcripts from the audio taping of the five sessions.

3. Informal clinical interviews of the subjects before and after each session.
4. Subjects' written notes made during each session.

5. Researcher's written notes made during each session and reflective notes made after each session.

6. Pre- and post-instructional assessments.

Structured Observations

The recorded interactions (video and audio) were the primary source for the verbal protocols. Simultaneous recording of computer interaction, student-student interaction, student interactions with materials, and verbal commentaries of students provided a more complete picture of what the students were doing as they developed greater understanding of the concepts.

Think-aloud verbal protocol is a list of verbal statements (transcript) made by the subject: It does not represent a complete record of the subject's thoughts or reasons for doing something (Larkin & Rainard, 1984). The protocol only provides indications of what the subject is thinking which means the researcher must infer a more complete model of the process. Think-aloud protocols as data are based on the premise that information that is reported verbally at the time of performance represents the information that the subject is attending to (Ericsson and Simon, 1993).

Collecting the protocols involves getting the subject to talk steadily and continuously about what he or she is thinking and doing. Termed concurrent verbal reports by Ericsson and Simon (1993), these protocols are the verbalized thoughts of the subjects with little if any additional processing. The researcher should only provide small amounts of neutral, nondirective speech that encourages dialogue; that is, the researcher needs to keep the subject talking.
without affecting the natural thinking processes (Larkin & Rainard, 1984). This procedure has several limitations and possible difficulties. These difficulties include the degree to which students verbalize, students failing to verbalize during the most critical, interesting, or revealing moments, utterances that cannot be understood, periods of long silences in which the subject may forget to verbalize or may not be able to verbalize (Jung, 1985), and the possibility that forcing students to speak aloud may lead the investigator to infer a greater degree of sequential processing than is actually occurring (Larkin & Rainard, 1984). However, this process has several advantages in that it stresses verbal data generated by the subject and it provides information about the cognitive processes without interfering with those processes.

To supplement the protocol data, both concurrent and retrospective reports were collected. Retrospective reports were gathered through an informal clinical interview method at the beginning and end of each session. According to Ericsson and Simon (1993), concurrent reports taken together with retrospective reports “are highly pertinent to and informative about subject’s cognitive processes and memory structures.” (p. 220).

**Clinical Interview**

Clinical interviewing, first developed by Piaget, involves questioning students about their knowledge and understanding. The clinical interview attempts to “ascertain the nature and extent of an individual’s knowledge about a particular domain by identifying the relevant conceptions he or she holds and the perceived relationships among those conceptions.” (Posner and Gertzog, 1982, p. 195). The information obtained is then represented in a suitable format, such as a semantic network or concept map, that is intended to be “a partial
representation of the individual's cognitive structure" (Posner & Gertzog, 1982, p. 195-196). Questions used during the interview are intended to be as non-suggestive as possible, to assure that the interviewer does not lead the subject or influence unduly the thinking of the subject. The most common type of questions are opened-ended ones. However, the interviewer may use "probing" questions that allow the interviewer to investigate in greater depth certain aspects of the subject's thinking.

Transcribing and Validation

The researcher transcribed the main group audio taped sessions. Several other persons transcribed two of the remaining groups. The last two groups, involved in the development of the tutorial, were not transcribed. The researcher checked the accuracy of each transcript by comparing them to the videotapes. In the process, the researcher supplemented the verbal protocols by noting in the margins subjects' behaviors, circuits being tested, and other actions and information. When a word or passage was indecipherable, the phrase "[TCH]" was used (transcriber can't hear). Words or passages that were not clearly understood were included in square brackets with a questions mark: [the bulb?]. Words or actions that were derived from the videotape were included in square brackets without a question mark: [setting up circuit].

Data Analysis:

Overview

Five pairs of students participated in the complete study: Three pairs participated in the preliminary trials and two pairs participated in the main study. For each set of students, approximately 300 pages of transcripts, seven hours of videotape, and several pages of subject/researcher notes were collected.
For all five pairs, the total amount of data is estimated to be 1500 pages of transcripts and 35 hours of videotape. Only one pair was analyzed for this report. The subjects' beginning mental models were inferred from the pre-instructional assessments and interviews. The subjects progressed through the five session instructional program, working over a period of several weeks. The average time for each session was approximately 60 minutes, ranging from 45 minutes to 90 minutes. At the start of each session, subjects were questioned on their previous work. At the end of each session, the subjects were asked to review and talk about what occurred. At the end of each day, the researcher reviewed the data from the videotapes, audio tapes, student notes, and observational notes.

Protocol Analysis and Concept Map Development

After the transcripts were checked for accuracy, passages were color-coded according to who was speaking and the nature of the interaction. Researcher comments were highlighted in pink. Passages that involved the subjects using information, applying concepts, or testing ideas were highlighted in blue. Passages in which the subjects were being presented with information, ideas, or concepts were not highlighted. Excerpts that contained examples of concept development, reasoning patterns used, or the use or misuse of analogies were outlined in yellow.

After color-coding the transcript, the researcher reread the pertinent passages and placed interpretations in the margins. Margins notes indicated concepts, ideas, and reasoning patterns used by the subjects and were made in red. The protocols and margin comments were re-evaluated while
viewing the videotapes of the subjects working together. Additional margin notes were made.

Using the complete protocol including margin notes, the major concepts and how they were related were listed on separate paper, referenced back to the protocol via session number and page number. The initial concept maps were developed using this information. After all concept maps were developed, the researcher compared the map to the original transcript and revised as necessary. **Reliability and Validity Issues:**

Reliability can be thought of as the degree of consistency in interpretation for a similar situation (Silverman, 1993). Reliability is obtained, in part, by detailing the context of the observations. To assure reliability of the researcher's interpretation of the data and development of the conceptual maps, a second researcher examined portions of the data and create her own version of the conceptual map independently. The two versions of the maps were then compared and contrasted. Although minor variations did exist, the two maps were very similar and represented the major concepts and relations to the same extent.

Validity is assured through several methods including examining data from a variety of sources. This study took data from audio- and videotaped interactions, subjects’ written notes, interviews, pre- and post-instructional tests, and researcher’s written observations. A second method to assure validity, or trustworthiness of the study, is to look for contrary or disconfirming evidence. There was no disconfirming evidence to suggest researcher bias.
Chapter 4

RESULTS AND ANALYSIS

Overview

Prior to discussing the results and analysis, an explanation of electric circuit behavior and the tutorial objectives including a conceptual map are discussed. To assist in interpreting the transcript excerpts, conceptual difficulties associated with electric circuits, reasoning patterns, and conceptual change theory is reviewed. Following the overview, the results are presented chronologically beginning with a discussion of the subjects' naive conceptions, followed by results from each tutorial session, and ending with the post-instructional assessment.

Circuit Behavior

An arrangement of a flashlight bulb, "D" size battery, and wire is an example of a simple direct current (D. C.) electric circuit. In such an electric circuit, energy is transferred from the battery to the bulb via the wires. A chemical reaction inside the battery transfers the negatively charged electrons from one terminal to the other, leaving a positively charged terminal and a negatively charged terminal. The separation of charges results in each terminal having an electric potential energy associated with it. Potential energy means that there is energy available. The difference in potential of the two terminals is called the battery's potential difference. The maximum potential difference is called the electromotive force or emf.

In addition to providing energy for the circuit, the battery creates an electric field within and parallel to the wire which exerts a force on the free electrons within the wire causing them to move. This movement of charge is
called an electric current. It is formally defined as the number of charges per unit time that passes through a surface that is perpendicular to the motion of the charges. The unit for current is the ampere (or amp). Because current is a consequence of potential difference, current is directly proportional to the voltage (potential difference) provided by the battery: more voltage, more current.

Current is also dependent on the total resistance of the circuit which is determined by the number of bulbs and how they are connected (the configuration of the circuit). Total resistance of a circuit is determined by finding the equivalent resistance of its elements. Current is inversely proportional to resistance. When bulbs are connected in series, one right after the other, total resistance increases and current decreases. When bulbs are connected in parallel, side by side (with their terminals connected together), total resistance decreases and current increases. Changing resistance in one part of the circuit will effect the total resistance of the circuit and, hence, change the amount of current.

The circuit shown in Figure 13, next page, has bulbs connected in series and in parallel. Bulbs A and C are in series. Bulbs D and E are in parallel with each other and, together, they are in series with bulb B. The branch consisting of BDE is in parallel with the branch consisting of AC. The bulbs can be rank according to their brightness: B > A = C > D = E. Bulb B is the brightest because the BDE branch has a lower resistance (and therefore more current) than the AC branch. The lower resistance is a result of the parallel bulb D and E, which have a lower combined resistance than the individual resistance of bulb C.
Conceptual Difficulties Associated with Electric Circuits

Students' conceptual difficulties are the result of beliefs based, in part, on personal experience. Table 6 summarizes the personal (and scientifically inaccurate) beliefs that were targeted in the instructional program.

Table 6 - Difficulties with Concepts Associated with Electric Circuits

<table>
<thead>
<tr>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Consumed</td>
</tr>
<tr>
<td>• Wires &quot;empty&quot; of current (charge) unless current is flowing</td>
</tr>
<tr>
<td>• Independent of circuit configuration</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential Difference:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Confused with current</td>
</tr>
<tr>
<td>• Indistinguishable with potential</td>
</tr>
<tr>
<td>• Failure to view battery as a constant voltage source</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Inability to distinguish between equivalent and individual resistance.</td>
</tr>
<tr>
<td>• Total resistance always increases</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circuit Configurations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Failure to see necessity of a loop (concept of a complete circuit)</td>
</tr>
<tr>
<td>• Identifying series and parallel connections</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Language Usage:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Failure to distinguish among associated concepts (e.g., charge &amp; current, current &amp; voltage, energy &amp; power) and tendency to use terms interchangeably</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formal Representations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Failure to recognize that a circuit diagram represents the electrical elements and connections, but does not represent its physical or spatial relationships</td>
</tr>
</tbody>
</table>
Tutorial Objectives

The five session tutorial was designed to challenge the subjects' prior conceptions associated with current, resistance, voltage, and the role of the battery. Appendix G illustrates the concept map for the fifth and final session of the tutorial. Specifically, by the end of the fifth session, the following conceptions were addressed:

- Circuit as a continuous, unbroken loop necessary for current to flow;
- Conductors and insulators;
- Conservation of current;
- Current as the flow of electrons and involving the transfer of energy;
- Current dependent on the total resistance of the circuit;
- Resistance and equivalent (total circuit) resistance;
- Parallel and series connections;
- Independent and dependent parallel connections;
- Battery as the energy source and the agent that drives the current;
- Battery as a constant voltage source; and
- Potential energy, potential difference, and emf;

Procedural knowledge included using a ammeter to measure current, using a voltmeter to measure potential and potential difference (voltage), reading simple electrical diagrams, and setting up circuits. Derivable equations included:

- Parallel: \( V_T = V_1 = V_2 = V_3, \ I_T = I_1 + I_2 + I_3; \) and
- Series: \( V_T = V_1 + V_2 + V_3, \ I_T = I_1 = I_2 = I_3, \) and \( R_T = R_1 + R_2 + R_3. \)
Reasoning Patterns Associated with Electric Circuits

Reasoning refers to the ability to qualitatively reason about a situation and is associated with the personal beliefs outlined above. Inaccurate or inappropriate reasoning patterns can be classified according to the nature of the reasoning (Licht, 1991). Table 7 summarizes the most common reasoning patterns used by the naive students. Appropriate reasoning that takes into account the complete circuit is termed holistic reasoning.

Table 7 - Naive Qualitative Reasoning Patterns

<table>
<thead>
<tr>
<th>Local/Sequential Reasoning:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• failure to recognize that changes in one part of the circuit will cause changes in other parts as well.</td>
</tr>
<tr>
<td>• bulbs farther from the battery will be dimmer with brighter bulbs closer to the battery.</td>
</tr>
<tr>
<td>• tendency to focus on one particular element, for example, a single light bulb, instead of the whole circuit.</td>
</tr>
<tr>
<td>• includes non-conservation of current.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanistic/Technical Reasoning:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• reliance on equations and using technical or mechanical methods to explain circuit behavior.</td>
</tr>
<tr>
<td>• assigning arbitrary numerical values to circuit elements in order to use familiar equations</td>
</tr>
</tbody>
</table>

Conceptual Change Theory

Table 8, next page, summarizes the major theoretical perspectives on conceptual change. For the purposes of this study, conceptual change will be studied as described by Carey (1985): Assimilation, or weak restructuring, in which relationships among existing ideas are changed but the original concepts do not change, and accommodation, or radical restructuring, in which an existing conceptual framework is reorganized and elaborated to accommodate new information (changes in concepts also occur). According to Dykstra et. al (1992), the conceptual maps provide a means of representing the processes of
assimilation and accommodation. Assimilation is represented when new cases are created under existing categories. Accommodation is illustrated through the changes in a sequence of two or more conceptual maps.

<table>
<thead>
<tr>
<th></th>
<th>Lower level</th>
<th>Higher Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pines &amp; West, 1986a</strong></td>
<td>Conceptual Development: • Integration and differentiation of knowledge into existing cognitive structures.</td>
<td>Conceptual Resolution: • Reconciliation of pre-existing ideas with conflicting situations.</td>
</tr>
<tr>
<td><strong>Norman, 1978</strong></td>
<td>Accretion: • addition of new knowledge into existing knowledge.</td>
<td>Restructuring: • Reorganization of existing knowledge into more appropriate frameworks.</td>
</tr>
<tr>
<td><strong>Dykstra, Boyle, and Monarch, 1992</strong></td>
<td>Differentiation: • new concepts emerge from more general concepts.</td>
<td>Class Extension: • existing concepts once thought of as different are found to belong to a broader class.</td>
</tr>
<tr>
<td><strong>Carey, 1985</strong></td>
<td>Assimilation or Weak Restructuring: • rearrangement of relationships among existing concepts. Concepts are not changed, only their applicability. Little if any change in the original framework.</td>
<td>Accommodation or Radical Restructuring: • Reorganization and elaboration of an existing conceptual framework to accommodate the new information. Involves changes in the concepts.</td>
</tr>
</tbody>
</table>
The Results

Overview

The results are presented in three sections: conceptual development, reasoning patterns, and analogy use and misuse. For the purposes of this study, the analysis focuses on four conceptual development areas: (1) current conservation, (2) current dependent on total resistance of circuit, (3) resistance in series and parallel and total resistance in a circuit, and (4) potential, potential difference, and the role of the battery. Throughout the study, it was evident that the subjects' reasoning patterns influenced conceptual change and development; therefore, subjects' type and use of reasoning is explored. Finally, because analogies were an integral part of the tutorial, an analysis of their use and misuse is presented.

Transcript excerpts and researcher’s analysis are presented within a two-column, double-lined format with the transcript on the left side and analysis on the right side, as shown in Figure 14 (left diagram). Tutorial excerpts including tutorial diagrams are presented within a shaded border (middle diagram). Subjects' notes are presented within a solid bold border and in block bold print (right diagram).

Figure 14 - Formats for Presentation of Data
Main Study Pair

Don and Heather were the main study pair. Both subjects were seniors, taking physics for the first time, and each had a GPA above 3.0. Heather was taking physics to fulfill a major requirement. Don was taking physics out of interest. This pair was selected because they had used a tested and revised version of the tutorial, talked freely and clearly, demonstrated a serious attitude toward participation throughout the study, and did not rush through any part of the study including the post-instructional assessment.

Pre-Instructional Assessment Results

Of the ten subjects participating in the preliminary trials and main study, all but one took the pre-test. Don, who was not enrolled during fall semester, did not take the pre-test. Don was one of the subjects in the main study group. However, based on his reported background, his interactions during the sessions, and the consistency of the pre-test results of his peers with similar studies reported in the literature, it is reasonable to infer that Don held preconceptions consistent with naive students. Appendix H contains the concept map for the naive model of Don’s partner, Heather. Her map is typical of naive students.

Concepts Held Prior to Instruction

As indicated by Heather's map, she held several misconceptions concerning electric circuits. Although she understood the need for a loop, she had difficulty in applying the concept appropriately. However, this difficulty may be more a function of not understanding the structure of the bulb rather than the concept of "circuit as a loop." There was evidence of confusing the terms energy, electricity, current, and power. In some instances, the terms were used interchangeably in the same problem situation.
The misconception that current is consumed was evident throughout the pre-test; for example, when describing the current at specific points in a single bulb circuit, as shown below, Heather viewed the current as decreasing around the circuit:

Q: Is the current at point 1 greater than, less than, or the same as the current at point 3?

<table>
<thead>
<tr>
<th>Subject's Responses</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Greater than. Number one is the positive end where the current is the most.</td>
<td>Focus is on location relative to the positive end (sequential reasoning), with implications of current being consumed.</td>
</tr>
</tbody>
</table>

Describing the amount of current in a two-bulb series circuit, Heather continues to view current as consumed, with the current most before the bulbs (nearer the positive terminal), lower between the two bulbs, and lowest past the bulbs, closest to the negative terminal.

Current was thought to be independent of the circuit configuration. Heather correctly thought that potential difference was a form of energy that is lost as heat. Although it was unclear if Heather was referring to current or
potential difference, she believed that more of it existed on the “positive” side of the bulb and less on the other side (an example of sequential reasoning).

**Reasoning Patterns**

The predominant reasoning pattern used by both Don and Heather was local/sequential reasoning. For example, comparing the brightness of a bulb in a single bulb circuit (bulb A) to the brightness of two bulbs (B and C) in series in a second circuit, Heather believed that the placement of the bulb in relation to the positive terminal of the battery would determine its brightness:

![Circuit Diagrams](image)

**Questions and Subject's Responses**

<table>
<thead>
<tr>
<th>Q: How does the brightness of bulb A compare to bulb B?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: The brightness should be the same. They both come from the positive line into the bulb.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q: How does the brightness of bulb A compare to bulb C?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: The brightness will be brighter in A than C. Bulb C must gain positive line from B, where as A’s line comes straight from the battery.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Q: How does the brightness of bulb B compare to bulb C?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Bulb B is brighter. It is getting a full power from the battery.</td>
</tr>
</tbody>
</table>

**Analysis**

<table>
<thead>
<tr>
<th>Local reasoning: focusing on one part of the circuit.</th>
</tr>
</thead>
</table>

Sequential reasoning: C is viewed as coming after B in the circuit.

Sequential reasoning: B is first in line and therefore receives “power” first.
Q: How would the brightness of bulb A change if a second, identical bulb was added to circuit I so that it was identical to circuit II?
H: It would depend on the placement of the bulb.
Sequential reasoning: brightness depends on bulb's order in the circuit.

The idea that current is consumed is also evident in the above responses. Local/sequential reasoning was most evident in Heather’s analysis of the combination series and parallel circuit shown below. Heather focuses on the position of the bulbs relative to the positive end of the battery, with changes in bulb brightness a function of where it is sequentially in the circuit.
Questions and Subject's Responses

<table>
<thead>
<tr>
<th>Q:</th>
<th>H:</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compare the brightness of each of the bulbs.</td>
<td>&quot;A should be the brightest. B &amp; C will be the same and D should be the less (sic). Each time energy is lost.&quot;</td>
<td>Sequential Reasoning: Bulb A is first in line, therefore receives the most &quot;energy&quot;.</td>
</tr>
<tr>
<td>Compare the current following through each of the bulbs.</td>
<td>&quot;Bulb A gets full current. It's using some and changing its form. Bulbs B &amp; C get the same amount and use some. Bulb D gets the least.&quot;</td>
<td>Sequential reasoning including current being consumed.</td>
</tr>
<tr>
<td>What happens to the current through bulb A if the switch is opened?</td>
<td>&quot;Nothing. It is not effected.&quot;</td>
<td>Local/sequential reasoning: Focusing on location of switch that is viewed as &quot;downstream&quot; from A.</td>
</tr>
<tr>
<td>What happens to the current through bulb B if the switch is opened?</td>
<td>&quot;I'm not sure. Right off I would think it was not effected because bulb D would be effected more.&quot;</td>
<td>Sequential Reasoning: Bulb B not effected because it is &quot;upstream&quot; from switch, whereas D is &quot;downstream.&quot;</td>
</tr>
</tbody>
</table>

There was no evidence of mechanistic or holistic reasoning based on the pre-test responses.

Session 1: Introduction to Electric Circuits

Tutorial Objectives

Session one focused on the concept of a circuit as a continuous loop through which "stuff" flows as indicated by the brightness of the bulb. To develop this conception, subjects explored conductors and insulators, difference between an opened and closed circuit, and the internal structure of the bulb.
Appendix C shows the concept map for this session. This session also provided the opportunity for the subjects to become familiar with the tutorial, the materials and other equipment (video camera, etc.), and with the setting.

**Overview of Results**

As indicated by the concept map (appendix I), the subjects demonstrated an understanding of a circuit as a continuous loop, distinguished between conductors and insulators, postulated that current was the flow of electrons, and that the battery provides the force to push the electrons. They were uncertain about the role of voltage. Although they believed that the electrons were not used up, they nonetheless indicated that current was consumed. They also believed that the battery was the source of electrons/current. Current dependency and series/parallel connections were not addressed during this session and were not evident in the subjects’ protocols.

**Conceptual Development**

The concept of a circuit as a continuous, unbroken loop was developed during this session. Once the subjects determined the necessity of the loop and which parts of the bulb were conductors and insulators, they easily inferred the bulb’s internal structure (Figure 15):

![Diagram of bulb](image)

**Figure 15 - Internal Structure of Bulb**
<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D:</strong> The glass is an insulator, the little black thing is an insulator ...</td>
<td></td>
</tr>
<tr>
<td><strong>H:</strong> ... black thing is an insulator, and the other two are conductors.</td>
<td>Both subjects are able to distinguish between conductors and insulators associated with the bulb.</td>
</tr>
<tr>
<td><strong>D:</strong> So this [metal side of bulb] connects to one of these two [internal support wires] and it goes up through and connects to that [filament].</td>
<td>Correct inference regarding internal structure of the bulb.</td>
</tr>
<tr>
<td><strong>H:</strong> So they [support wires] are both conductors.</td>
<td>Correct inference regarding type of material.</td>
</tr>
<tr>
<td><strong>D:</strong> Yeah, and the little ... that piece [colored glass holder] is obviously an insulator because its touching both [support wires], right the little white piece?</td>
<td>Correct inference regarding the filament.</td>
</tr>
<tr>
<td><strong>H:</strong> Yeah insulator.</td>
<td></td>
</tr>
<tr>
<td><strong>D:</strong> So that’s a conductor [filament], that little piece because that’s what illuminates.</td>
<td></td>
</tr>
</tbody>
</table>

Perhaps one of the most difficult concepts for students is that of potential energy and the role of the battery. Although they may be familiar with the term voltage, its meaning was elusive. Don and Heather provided this explanation for the purpose of the battery:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H:</strong> It’s the power source.</td>
<td>Battery as source of electrons.</td>
</tr>
<tr>
<td><strong>D:</strong> Yeah, it provides the ...</td>
<td>Probing Question</td>
</tr>
<tr>
<td><strong>H:</strong> ... electrons ...</td>
<td></td>
</tr>
<tr>
<td><strong>D:</strong> the source of “stuff” the electrons</td>
<td></td>
</tr>
<tr>
<td><strong>R:</strong> And what happens when a battery goes dead?</td>
<td></td>
</tr>
<tr>
<td><strong>H:</strong> It runs out of electrons [laughing] uh, I don’t know. Why does it go dead?</td>
<td></td>
</tr>
<tr>
<td><strong>D:</strong> Actually, I don’t know, cause it can’t ...</td>
<td></td>
</tr>
</tbody>
</table>
H: But you can recharge them.
D: ... it can't lose energy, can it?
H: It can every time, well it takes energy to burn the bulb, so it will lose energy won't it?
R: So what is being used up?
D: Well, actually, it just loses the force, it loses whatever force propels the electrons through the system, right? It doesn't actually lose electrons, right?
R: I'm not going to say.
D: OK, I think it just loses its ability to propel the electrons and force the electrons through the system, I guess...
R: Any idea on where the electrons originate from?
D: uhm, they don't really originate anywhere, do they? It's kinda like a fluid system, they're just moved through, they're constantly in all the parts, right?
H: Yeah
D: And the electrons that are pushed out of the battery, push the electrons that are in the wire through the wire, and push the electrons in the bulb right now out of the bulb, the same electrons.
H: Wouldn't more electrons have to come from this [the battery] though? Or you could do this with any object?
D: But for every one that goes out, one goes in the negative end.
H: True
D: not the positive end.
H: But only in the battery. You can't do it with two metal circles and a light bulb.
D: True

Probing Question
Uncertain about what is being used up, but he doesn't believe it's current.

Probing Question
Accurate representation of where electrons are found.

Battery as the source for the electrons.

The battery is necessary to light the bulb, therefore, ...
H: So the electrons have to come from a source.
D: That just pushes it through. Right?
H: True

she views the battery as being the source of the electrons.
Although, agreeing, she is still unconvinced (tone of voice).

Reasoning Patterns

The subjects used local /sequential reasoning during this session. At the end of the session, the subjects were instructed to think back to what they had learned, talk about what they considered to be important information, and then decide which bulb or bulbs in the circuit shown below would light and their relative brightness:

![Circuit Diagram]

Transcript

<table>
<thead>
<tr>
<th>Line</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: That one [A] and that one [C], those two. Well, couldn't, no that one [B] won't. Those two [A and C].</td>
<td>Referring to which bulbs are lit. A and C will light.</td>
</tr>
<tr>
<td>D: I would assume these two [A and C] would be half as bright than normally, cause there are two of them.</td>
<td>Comparing brightness of the two bulbs to a single bulb in a one-bulb circuit.</td>
</tr>
<tr>
<td>H: Isn't this one [A] getting full current? To there?</td>
<td>Sequential Reasoning: A gets “full current” because it's first in line.</td>
</tr>
<tr>
<td>D: But the battery has to power both.</td>
<td></td>
</tr>
<tr>
<td>H: Yeah, that's true. I don't know.</td>
<td></td>
</tr>
</tbody>
</table>
There was no evidence of mechanistic or holistic reasoning during this session.

**Analogy Use and Misuse**

No analogies were presented via the tutorial and there was no spontaneous use of analogies during this session.

**Session 2: Introduction to Current**

**Tutorial Objectives**

The concept of a circuit as a complete loop was expanded to include the idea that current makes a round-trip journey. The flow of “stuff” was defined as a current. The conceptions of current conservation, its dependency on the circuit configuration and series and parallel connections were introduced. The water circuit analogy was used to explain circuit behavior. Appendix D shows the concept map for this session.

**Overview of Results**

Subjects’ recognized the round-trip nature of current flow, began to weakly understand that current was not “used up” and that it is dependent on circuit configuration. However, they continued to hold on to and use the misconceptions of current consumed and independent of configuration. They could recognize the difference between series circuits and parallel circuits; however, they had difficulty in setting up parallel circuits and describing the flow through a parallel circuit. The junctions proved particularly challenging. There was no change in their understanding of voltage and they continued to view the battery as the current source (see appendix J).
**Conceptual Development**

The subjects continued to gather data concerning the behavior of current in a simple circuit. Although the concept of a circuit as a continuous loop was established previously, the subjects did not know whether the flow was unidirectional, bi-directional, or round-trip (going around and around). The circuit as a round-trip flow was relatively easy to establish by having the subjects investigate the uniform heating of a piece of wire connected directly across the terminals of the battery. When critiquing two different beliefs as presented by fictitious students, this understanding was demonstrated:

The first student believes that when a bulb is lit, the electricity flows from the battery to the bulb, and that there is an equal flow from the bulb back to the battery.

The second student believes that electricity flows only from the battery to the bulb because a battery can light a bulb, but a bulb can’t do anything without the battery.

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: I still think the first one is true. If the bulb is pushing the stuff</td>
<td>Current makes a round trip through circuit.</td>
</tr>
<tr>
<td>through the light back into the battery, it’s doing both.</td>
<td>Battery as source of electrons</td>
</tr>
<tr>
<td>H: But this [battery] has the stuff</td>
<td></td>
</tr>
<tr>
<td>D: Yeah, but still</td>
<td></td>
</tr>
<tr>
<td>H: But that’s the reason this won’t light other stuff. Because a battery</td>
<td></td>
</tr>
<tr>
<td>can light a bulb but a bulb can’t do anything without the battery</td>
<td></td>
</tr>
<tr>
<td>D: True</td>
<td></td>
</tr>
<tr>
<td>H: Because you can’t take this [another bulb] and two other wires and light another bulb.</td>
<td></td>
</tr>
<tr>
<td>D: True, I think it is the first one.</td>
<td></td>
</tr>
<tr>
<td>H: Yeah, I believe the first one.</td>
<td></td>
</tr>
</tbody>
</table>
D: I think first. I think it's more equally that, it's just being pushed along through the circuit by the battery.
H: Uhm hum.

Battery as the "driving force".

Note how Heather continues to hold on to the idea that the battery is the source of electrons, using the information presented via the second "student" to support her idea. A student's ability to selectively attended to information based on personal theories or experiences is one factor that makes conceptual change teaching a challenge and emphasizes the need to consider students' prior knowledge during instruction.

During this session, the subjects began to understand that current is not "used up" rather they believe the current is "shared" among the bulbs. However, it is difficult to know what they meant by "shared." They also demonstrated a continued belief in current being consumed.

The idea that the amount of current can be different in different circuits is difficult for most students, including Don and Heather, to understand. In the next passage, the subjects were asked to compare current through bulb A in a single-bulb circuit, with the current through bulb B in a two-bulb parallel circuit. This passage also illustrates their difficulty with series and parallel connections. They were instructed to think about the water analogy as they explained their answer.

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: It's the same. Same.</td>
<td>Correct.</td>
</tr>
<tr>
<td>D: I was just trying to think about it. Look at this. Half the water would go each way.</td>
<td></td>
</tr>
</tbody>
</table>
H: But what if the water pressure is the same in all the pipes? ... The pipes are going to be full of water no matter what, so what if this pipe is full of water and that pipe is full of water, they’re both full of water. They’re both going to be the same.
D: What I’m saying is that instead of 100% of the water going through A, only half of the water goes through B and C.
H: Then the bulbs wouldn’t be the same brightness. These two would be less bright than that.
D: hum ...
H: Does the current... I’m not quite sure what you’re saying.
D: That’s true ...
H: Not unless you putting out the exact same amount of water. Then you would have an extra pipe to get through.
D: hum?
H: Cause you only have one pipe here, and two pipes here. If you are putting out the same amount of water each time ...
D: That’s what I’m saying. The same amount of water would be going through here, would be going through here and here.
H: No, I wouldn’t think the pipes would be full. As long as the pipes are kept full ...
D: Well they would be full, but it would be half the flow. I would think.
H: If they’re full, then the flow would be the same. You would have to have less water to have less flow.
D: I think I’m confusing myself.

Heather correctly perceives the analogy, with the pipes full of water.

She is implying a constant water source, or, in the case of the electric circuit, the battery as a constant current source.

This passage also illustrates a difficulty associated with this analogy.
When asked to describe the flow at the junctions where the current splits into the two parallel branches, the subjects still required assistance to understand what was happening. In this situation, the researcher posed both probing questions and clarifying statements to supplement the tutorial directions.

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Obviously nothing happens because the light bulbs [are equal?]</td>
<td>Local Reasoning: Focusing on the bulbs only.</td>
</tr>
<tr>
<td>D: An equal amount?</td>
<td></td>
</tr>
<tr>
<td>H: its going to be the same amount here ...</td>
<td>Referring to the junctions.</td>
</tr>
<tr>
<td>D: Yeah, the same amount that comes in here, leaves in both directions.</td>
<td></td>
</tr>
<tr>
<td>H: Yeah,</td>
<td></td>
</tr>
<tr>
<td>R: Say that again.</td>
<td></td>
</tr>
<tr>
<td>D: The same amount that comes into the junction, leaves in both directions.</td>
<td>Still focusing on the bulbs' behavior.</td>
</tr>
<tr>
<td>R: So all three of those wires have the same amount in it?</td>
<td>Probing Question</td>
</tr>
<tr>
<td>D: I think so.</td>
<td></td>
</tr>
<tr>
<td>H: It would have to for both the bulbs to have the same brightness. Not unless this one had more than these two. These two would have to be the same. But this one doesn’t.</td>
<td>Still focusing on the bulbs' behavior.</td>
</tr>
<tr>
<td>D: Yeah, that’s what I was thinking about with the water ...</td>
<td></td>
</tr>
<tr>
<td>H: This one will have more, than this one and this one.</td>
<td></td>
</tr>
<tr>
<td>R: What? Say it again.</td>
<td></td>
</tr>
<tr>
<td>H: This one would have more than this and this. These two have to be the same, because these two have to be the same for the bulbs to be the same.</td>
<td>Beginning to realize that for two pipes to have each flow, the pipe connecting them would have to have double the flow.</td>
</tr>
<tr>
<td>D: OK, but..</td>
<td></td>
</tr>
<tr>
<td>H: This one doesn’t necessarily have to be the same as these two.</td>
<td></td>
</tr>
<tr>
<td>R: In fact, it’s how much more?</td>
<td>Probing Question</td>
</tr>
</tbody>
</table>
H: This could be twice as much as this or this.
D: But that can’t be though, cause ...
H: cause then the bulbs wouldn’t be the same as the one bulb ...
D: Yeah, if there was no bulb C, then this would equal this. And this bulb would be X amount ...
H: Yeah, so then they all three would have to be the same ...
D: ... would be so bright but if they are in parallel this one would still equal this one cause it’s just as bright, so it must equal that too.
H: So they would have to be the same.
R: Did you not find that the single bulb was the same brightness as those two? Clarifying Statement
H/D: Uh uhm.
D: That’s what we’re saying, with a single bulb, there’s no bulb C, the amount of current flowing through this wire would have to equal this wire. Right?
R: If there was no bulb C? Correct. Clarifying Statement
D: Right, no bulb C. So that would be ...
H: So that’s the same brightness as bulb C
D: So if they’re the same brightness ...
R: Then how much is flowing through that part of the circuit right there? Probing Question
H: The same ...
D: This would equal both of these.
H: Yeah, the same.
D: It should. If there’s no difference in brightness.
H: Cause they’re the same
R: But if it’s splitting? Probing Question
D: Something’s dividing in half. [laughing] I don’t know what though.
R: OK Recognizes that something is splitting at the junctions.
D: Do equal voltages go to each bulb, but half the [pause] amperage I guess?
H: Isn’t there a certain amount you needed to light the bulb. A certain [threshold?] or something like that? As long as you got that amount they brighten the same even if ...
D: They can be brighter. Except you can dim the bulb and brighten the bulb.
H: That’s true. Then that’s got to be the same as the other two.
D: So whatever causes it to be bright is equal and something else may be dividing in half. I guess
H: Continue

Possibly recognizes that current can vary ...
but is unwilling to believe that the current would be the stuff that is dividing.

The interesting part of this passage is where the subjects’ pose an alternative explanation ("something else may be dividing") for what they are seeing instead of the explanation that is supported by the data but in conflict with their original naive conception of current being independent of the configuration of the circuit (the circuit’s total resistance). The subjects were then asked to compare the current passing through the battery in each circuit:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: It’s the same. It would have to be the same or the bulbs wouldn’t be as bright.</td>
<td>Views the battery as a constant current source.</td>
</tr>
<tr>
<td>R: You know the current through the bulbs are the same because they’re the same brightness ...</td>
<td></td>
</tr>
<tr>
<td>D: But they’re the same brightness as the single bulb circuit.</td>
<td></td>
</tr>
<tr>
<td>R: Uhm hum.</td>
<td></td>
</tr>
</tbody>
</table>
D: So you would think each bulb in the single bulb circuit, or each bulb in the parallel circuit is receiving the same amount of current as the bulb in the single bulb circuit.

R: *uhm hum.*

D: So they [the bulbs] should all three be equal, receiving equal current.

Local reasoning is also evident as subject is focusing on what is happening to the individual bulbs and not the entire circuit.

Don was beginning to see how the battery could deliver different current amounts: "I didn’t really think about it [battery] having multiple levels of output. So it can be variable ... the battery is capable of putting out double the amperage so each bulb gets the same amount...". However, he was uncertain about its relationship to resistance: "... variable current can flow through the battery kind of regardless of resistance."

**Reasoning Patterns**

The first use of bipolar reasoning, a form of local/sequential reasoning, was evident in their explanation of a series circuit. Bipolar reasoning views current as flowing from both terminals of the battery, meeting at the bulb, and being consumed. The subjects were asked to explain why bulb A is brighter than bulbs B and C:

![Series Circuit Diagram](image)
<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: Oh, the current should be between bulbs B and C...</td>
<td></td>
</tr>
<tr>
<td>H: ... it [A] gets full current</td>
<td></td>
</tr>
<tr>
<td>D: If its resistance, its going through double the resistance.</td>
<td></td>
</tr>
<tr>
<td>H: Why isn’t bulb B brighter than bulb C?</td>
<td></td>
</tr>
<tr>
<td>D: Cause its a circuit,</td>
<td></td>
</tr>
<tr>
<td>H: Its continuous?</td>
<td></td>
</tr>
<tr>
<td>D: Yeah, its not necessarily hitting bulb B then bulb C</td>
<td></td>
</tr>
<tr>
<td>H: ... hitting both sides ...</td>
<td></td>
</tr>
<tr>
<td>D: Neither one might until a complete circuit is made ...</td>
<td></td>
</tr>
<tr>
<td>H: ... until a complete circuit. OK</td>
<td></td>
</tr>
</tbody>
</table>

Although not describing it in terms of sequential flow, there is not enough evidence to judge it as holistic reasoning. Bipolar Reasoning: Current flowing from both terminals.

Local reasoning was the predominate reasoning pattern used. An example is evident in the subjects’ explanation as to why a single bulb circuit and two bulbs in a parallel circuit are equally bright, as shown below:

![Diagram](image)

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: uhm, they’re both basically connected straight to the battery. The resistance ...</td>
<td>Local Reasoning: Focusing on how each individual element is connected, and ...</td>
</tr>
<tr>
<td>H: It doesn’t go through the resistance.</td>
<td>not on how the entire circuit is affected. Both subjects are focusing on</td>
</tr>
</tbody>
</table>

95
D: Yeah, it doesn't have to go through double the resistance.
H: OK  the individual resistances and are failing to consider the total resistance of the circuit to explain bulb behavior.

**Analogy Use and Misuse**

Perhaps the most difficult concept the subjects dealt with in this session was the idea that the amount of current flowing in a circuit can change and how the current behaves at junctions. The water analogy was not completely helpful:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: ... now we know the battery can change its flow, we don't know how. We still don't know how it knows how many light bulbs are connected to it. I mean, how does it know if there's another one connected to this one and it has to give off more to light both?</td>
<td>Does not understand relationship between current and total resistance of circuit.</td>
</tr>
<tr>
<td>D: I think why we are screwing up with parallel circuit, uhm, parallel water circuit ... I think I was thinking of the pump, pumping water through the circuit so that it kinda had a maximum point, but the reservoir won't. If there is little resistance, the reservoir would be barely filled so that water would push the other water through. If there was more resistance, it would just take more water to fill up, or it would fill higher with water before it would flow through. You know what I mean?</td>
<td></td>
</tr>
<tr>
<td>H: But the reservoir is always kept full.</td>
<td></td>
</tr>
<tr>
<td>D: uhm hum</td>
<td></td>
</tr>
<tr>
<td>H: So there is always enough water.</td>
<td></td>
</tr>
</tbody>
</table>
D: Yeah, I was thinking of it in reverse, where the battery was acting like the pump where it could only pump out so much. I guess the battery can since it is also variable.
H: OK.

Session 3: Exploring Current Behavior Qualitatively

Tutorial Objectives
The subjects continued to explore current behavior qualitatively, by observing relative brightness of bulbs in different circuits and within the same circuit. Conceptions of current conservation and current dependent on configuration were developed further. Series and parallel circuits were investigated with the conception of independent parallel branches introduced. The role of the battery was introduced by examining circuit behavior when two batteries are connected in series and in parallel in different circuits. The chemical reaction inside the battery and its relationship to the current was mentioned. The lighting of the bulb was explained. The teeming-crowd analogy was introduced to explain current flow through series and parallel connections. See appendix E for the concept map.

Overview of Results
Subject understanding of current dependency on configuration increased although they still used their prior "current independent" conception (see appendix K for concept map). Related to that misconception, a new misconception was evident: They began to explain some circuit behavior by viewing the battery as a constant current source. They continued to view the battery as the source of current. However, they could not decide whether the
wires were “filled with current” (charges) or not. Current conservation remained in conflict with current being consumed, although the latter idea was weaker. The subjects did demonstrate an understanding of independent parallel branches, but continued to have difficulty in building circuits containing parallel connections.

Although the subjects understood that the bulb brightness was due to electrons colliding inside the filament causing the filament to heat and glow, they erroneously concluded that the friction of the filament was a function of its resistance only and not of the current amount flowing through it. This misconception may have been the result of not completely understanding the relationship between current and resistance. This model of bulb behavior is evident in later sessions as well.

By this time, the physics course work began to address electric circuits. At the beginning of this session, Don and Heather reviewed what occurred in the physics lab where they were presented with equations explaining current behavior and resistance in series and parallel circuits:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Now what did we learned today?</td>
<td>Referring to the physics lab</td>
</tr>
<tr>
<td>D: That voltage was added up between the two ...</td>
<td></td>
</tr>
<tr>
<td>H: Yeah, it was the same over here. So this voltage equals, if we had another voltmeter here ...</td>
<td></td>
</tr>
<tr>
<td>D: Actually, the voltage -- this voltage plus this voltage equals the total voltage.</td>
<td>Referring to a series circuit, where the total voltage equals the sum of the individual voltages, one of the equations the students learn in class.</td>
</tr>
<tr>
<td>H: Equals the total voltage.</td>
<td></td>
</tr>
<tr>
<td>D/H: But this voltage and this voltage ...</td>
<td>Referring to a parallel circuit, where the total voltage and each individual voltages are equal.</td>
</tr>
<tr>
<td>D: ... are equal to this voltage.</td>
<td></td>
</tr>
<tr>
<td>H: Right.</td>
<td></td>
</tr>
</tbody>
</table>
D: Resistance they're just added, and this is one over the total equals one over each of the individual resistance.
H: We had I up on the board. What was I?
D: I is the current.
H: So the current for parallel is ...?
D: These two added ...
H: These two added but the current ...
D: But they're not necessarily equal. They could be .8 and .2 and that would be one.
H: But the current for this one is the same. In one of them, the current was equal. One had I total equals I one I two, and that was serial. Isn't that right? [to R]
D: Current?
R: In a series circuit the current is going to be the same throughout.
H: So I total is going to equal this. But in this, its I one plus I two equals I three equals I, in the parallel.
D: This should help us here. Maybe we can found out the answer to my volt question.
H: uhmm hum. Continue.

Referring to parallel resistance and its equation:
\[ \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + ... \]

Referring to the equation for current in a series circuit:
\[ I_T = I_1 = I_2 = ... \]

Referring to the equation for current in a parallel circuit:
\[ I_T = I_1 + I_2 + ... \]

Mechanistic/technical reasoning became dominate as a result of having the equations available. Local/sequential reasoning continued to be used. The first evidence of holistic reasoning was demonstrated during this session.

**Conceptual Development**

Conceptual change requires the student to become dissatisfied or disequilibrated with his or her existing conception. Some of the circuits selected for the tutorial were designed with this requirement in mind. For example, although the subjects were familiar with a simple two bulb series circuit, like the one shown one the left (next page), they were unable to correctly predict how
bulb A would change when another bulb was added in parallel to bulb B, as shown in the circuit to the right.

When bulb C is added in parallel with bulb B, the overall resistance of the circuit decreases and current increases. As a result, the brightness of bulb A increases. The following excerpt illustrates how Don and Heather were surprised by the result and how they tried to understand what was happening:

Add another bulb of the same type, bulb C, in parallel to bulb B as shown below. BEFORE you close the switch, use your model to predict the relative brightness of the bulbs. Do you expect the brightness of bulb A to change and if so how? Explain. When you are ready, close the switch and click continue.

**Transcript**

| H: A should be the same, shouldn’t it? | Subjects making their predictions. |
| B and C will change.                      |                                  |

100
D: A will be twice as bright as B and C.
H: I think A will be the same as this [B] and this [C] will just get dimmer.
D: That's right, A will stay the same, and
H: B and C will be half as bright/dim [setting up circuit]
D: A got more bright. A got brighter.
H: That's because those went out.
D: That's weird.
H: There's something wrong with that one.
D: The other two went out, they're basically half as bright, but that's brighter.
H: No, those are pretty much out.
D: Well, yeah, there's not enough current to light the bulb.
H: Why did this one [A] get brighter? I thought this one [A] would stay the same and those get half [B and C]. But it got brighter. [pause]
R: So what happens if you unscrew C?
D: Unscrew C?
H: This one goes down [A] and this one [B] will light.
D: Yeah. Now they're equal again.
H: They're the same. So that's A and, well that just makes A and B in series.
D: That's right. These got brighter but I don't understand why that one got...
H: I don't understand why that one [A] got brighter [with C].
D: These should get dim [B and C], that should get half as dim [B] and equal this one [C]. But I don't understand why that one [A] got brighter. [pause]

Local reasoning: The change will only affect bulb B, the one that bulb C is being connected to.

Both subjects were startled with the fact that bulb A increased in brightness, opposite to their prediction.

Question posed after a pause.

The opposite of what happened when bulb C was added.

Local reasoning.
R: Is there current flowing through B and C even though they are not lit?
D/H: Yes
H: It's just not enough current to light it. Why did they get brighter? I thought they would stay the same.
D: Is there some type of threshold they have to reach for the bulb to light?
H: But why would that matter?
D: Cause I'm trying to explain why A got brighter. What I'm thinking is that it might go to a certain point and then the bulb lights. If it doesn't light, there is still current being used up. I don't know, something...
H: So it's all being used by A?
D: ... something that could be passed.
R: So why would A get brighter? [pause] What would cause any bulb to brighten?
D/H: More current
R: And why would the current change?
D: I would think it shouldn't. It's still going through...

R: Well, but why would it, in any situation, why would the current change?
D: Less resistance.
R: So how does that apply to this situation? [pause] What do you know about parallel versus series?
D: OK, these are hooked in parallel, so its the inverse of these, so there is actually less resistance here while they're in parallel than one single bulb in series.
H: Oooh, so if you took, like he said in class, if you took this out and considered it one, and made it in series, it would be less resistance.

Question posed after a pause.

Instead of considering how the resistance is changing, he is presenting an alternative explanation based on how the bulb may function.

Current consumed.

Probing question presented to refocus their attention on why a bulb lights.

Misconception of current independent of circuit configuration continues to be firmly held.

Mechanistic Reasoning: Relying on the equation for resistances in parallel.
D: It would be actually less, so the total of B and C is actually less than B or C individually.
H: Yeah, cause they're in parallel.
D: That's weird.
H: Isn't it though?

This reaction was common to all subjects.

At this point, the subjects seemed stuck. The researcher asked the subjects to consider the teeming-crowd analogy and how the people moved through A, B, and C. In this situation, the analogy seemed to help the subjects explain what was happening in the circuit:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: They would have more places to go. So they'll go through B and C quicker than they would go through A so its less resistance.</td>
<td>More paths, implying less resistance.</td>
</tr>
<tr>
<td>D: That's true.</td>
<td></td>
</tr>
<tr>
<td>H: And if you have less resistance, then that makes A brighter.</td>
<td>Less resistance means more current and a brighter bulb.</td>
</tr>
<tr>
<td>D: That's true. OK.</td>
<td></td>
</tr>
</tbody>
</table>

However, a new dilemma arose which was typical of one of the difficulties the subjects had as a consequence of local reasoning: If there was more current because of less resistance, then why were bulbs B and C not lit?

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Why isn't there enough current for B and C to, if there's less resistance then why isn't there enough current for B and C to brighten though? [pause] If there is less resistance, why aren't they lit? [pause]</td>
<td>With local reasoning, as exhibited here, the subjects are focusing on a particular part of the circuit. If bulb A has more current flowing through it, why do bulbs B and C not light? The subjects fail to recognize that the total current is split between bulbs B and C,</td>
</tr>
</tbody>
</table>

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Three of the five participating groups posed a similar alternative explanation of bulb behavior based on the bulb's resistance changing instead of the total resistance of the circuit and the paths available. At this point the researcher intervened:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>R: <em>But the bulb's resistance isn't going to change that much. It will change some due to the heating effects, but not much. [pause] Is the amount of current going through B the same as A?</em> [pause]</td>
<td></td>
</tr>
<tr>
<td>H: No [tentatively]</td>
<td>Failure to remember that the bulb's resistance does not change. Even though he disagrees, he continues by offering an alternative explanation to the bulb lighting, based on its resistance. However, he also recognizes that his explanation is inadequate but cannot offer another one. Again, local reasoning may be influencing his inability to explain why bulb A brightens.</td>
</tr>
</tbody>
</table>
D: B and C yes,
H: B and C are the same.
D: B and C would be yes. A and B, current. No, because they’re in series, it would have to be added. Not necessarily added because, the total of B and C, the current going through basically the unit of B and C would have, that plus A would have to equal the total current.
H: would equal, Cause...
R: That plus A or B and C is what’s going through A? Imagine the people going through there
D: In series...
H: Well if for every one...
D: ... the current is total
H: It could be half, cause for every two people who go through A, one can go to B and one can go to C. So B and C, so B would be half of A. Know what I mean? If you have people going down through A?
D: Yes
H: If you have one person go down, he can go to B, but then if you have another person come down, he can go to C. So for every two people going down through A, one goes to B and one goes to C. So B would be half of C, I mean B would be half of A but B and C would be equal.
D: They would be half, these [B and C] would each be half of A. So these would be like...
H: So you have to have...
D: ... five five and that would be ten, so the overall current would be 20

Might be mechanistic reasoning.

Not understanding what was said, a clarifying question was posed along with a reminder of the analogy.

This response may be due in part to the belief that current is consumed.
In the previous interaction, it is evident that the subjects remain uncertain about flow through a parallel circuit and how the current splits or divides at the junctions.

**Reasoning Patterns**

After correctly predicting the brightness of a bulb when two batteries are connected in series, the subjects used predominately mechanistic reasoning to explain the circuit’s behavior:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H</strong>: Hello, twice as bright.</td>
<td>Mechanistic Reasoning: Reliance on an equation, in this case, Ohm’s Law of V=I/R.</td>
</tr>
<tr>
<td><strong>D</strong>: Twice as bright.</td>
<td>Inappropriate use of equation.</td>
</tr>
<tr>
<td><strong>H</strong>: So isn’t that cool. So what happens to the current?</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong>: So the current. The current is the same, the voltage is doubled, I think.</td>
<td></td>
</tr>
<tr>
<td><strong>H</strong>: The voltage is doubled.</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong>: No, it should be double the current though, because the bulbs are twice as bright. The current is the stuff, remember?</td>
<td></td>
</tr>
<tr>
<td><strong>H</strong>: Current, so it would be double the current.</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong>: Its double the current.</td>
<td></td>
</tr>
<tr>
<td><strong>H</strong>: So its twice as many electrons.</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong>: I guess it’s twice the current and twice the voltage. It has to be both, because V=, is it V = I over R or R over ..?</td>
<td></td>
</tr>
<tr>
<td><strong>H</strong>: Well, if V doubles then the resistance would have to double.</td>
<td></td>
</tr>
<tr>
<td><strong>D</strong>: True. So, yeah, so if current doubles, voltage doubles</td>
<td></td>
</tr>
<tr>
<td><strong>H</strong>: Then resistance would double.</td>
<td></td>
</tr>
</tbody>
</table>

As shown by the interaction, one problem with mechanistic reasoning occurs when the students do not understand the conceptual basis of the equation.
In this case, the subjects do not understand which resistance should be considered and fail to recognize that bulb resistance does not change significantly in a circuit.

The belief that the battery was a constant current source, that is, that the current does not change, was strongly held. From the previous session, the subjects began to demonstrate how it was possible for the current to change. However, even in this session and with the aid of equations, the subjects still had difficulty believing that the current could change. When asked to describe how the current through the battery changes as more and more bulbs are added to the circuit in series, the subjects' response was:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: That stays the same, right? It's just distributed among, eventually, too many bulbs, right?</td>
<td>Battery as a constant current source.</td>
</tr>
<tr>
<td>H: Wouldn't it try to put out more current until it maxed?</td>
<td></td>
</tr>
<tr>
<td>D: See that's what it appeared to be.</td>
<td></td>
</tr>
<tr>
<td>H: Because in parallel, it just sticks out more current to light each one. Why in series doesn't it stick out more current to try to light them all until it maxes out? Cause in parallel, if you can added them up or what ever, because well, they're all the same. So, if you could, if</td>
<td></td>
</tr>
<tr>
<td>D: So I would equal [pause]</td>
<td></td>
</tr>
<tr>
<td>R: Well the current through the branches in the parallel circuit don't necessarily have to equal. They just need to add together to equal the final total current flowing through the entire circuit.</td>
<td></td>
</tr>
<tr>
<td>H: Yeah, so you just do it until you max the battery. Cause doesn't the battery increase the current flow?</td>
<td></td>
</tr>
</tbody>
</table>
R: Well the amount of current is dependent on the resistance of the circuit, in this case the resistance of the number of bulbs and how they're connected. So if the current is decreasing because you are adding more and more bulbs, then the total current through the circuit is changing.

D: Then the current through the battery has to be less too.

H: Uhm hum.

D: Since its a continuous system. Cause if you look at that, the greater the resistance, that goes to almost zero, so the current goes to zero, with the I equals V over R.

H: Didn't we say last time that the battery changes...

D: We thought its, we thought the battery would change, that was how we explained, we never did explain how, why these are so dim. If these were in parallel they would all be just as bright. Why can't the battery [pause] cause the battery has to send out enough flow to make those three bright that way, why can't it send out more if it would change.

R: But how does the resistance change as you add things in parallel?

H: They don't really.

R: Well, they do, but

H: But not as much as it do in series.

D: The inverse of the

H: The inverse of it, but in series you add the actual resistances.

D: The inverse of the resistances

R: So the total amount of current in a circuit depends on the total amount of resistance in the circuit.

Mechanistic Reasoning: Relying on equations to explain phenomena.
H: So the battery doesn’t change how much it sticks out each time.
R: Well, in essence it does, but it depends on how the circuit is configured.
H: But in series it’s obviously too much [pause] resistance, cause it goes out after, it may take one more bulb.
D: That’s true cause what we had here ...
H: They were pretty dim.
D: ... basically resistance going to infinity which then the current would basically be zero, with the more bulbs we add, do you agree?
H: Yes.
D: So the bulb, so the actually current through the battery would be less also.

As indicated in the section on concept development, the ideas that current is dependent on the total resistance of the circuit and that resistance will actually decrease when a bulb is added in parallel are very difficult for students to understand. While the subjects were attempting to reconcile what they saw with what they knew, the first evidence of holistic reasoning occurred:

3) Given that the amount of current through bulb A is the same amount of current that is going through the battery, how does the amount of current through the battery change as bulb C is added in parallel with bulb B?

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
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</thead>
<tbody>
<tr>
<td>D: More current through the battery since there is less resistance. Right?</td>
<td>Recognizes that current is dependent on resistance.</td>
</tr>
<tr>
<td>H: Yeah. [tentatively] D: OK. So there’s, so there’s more current, but each is getting half. Know what I mean?</td>
<td></td>
</tr>
</tbody>
</table>
H: Yeah, there's less resistance.
D: There's more current through the whole system, but each of these is only getting half of the total current. Know what I mean? And that must not be enough to light the bulbs.
H: I thought you just said more current went through those? Not enough resistance, more current?
D: More current through the system, the overall system, but half of the current of the total system is going through each of these.
H: And that's not enough current to light them?
D: I guess not.

Here, Don refers to the total current instead of the current flowing through an individual bulb.

Heather, however, is still focusing on the alternate explanation based on resistance of bulb. Don recognizes that even though the total current of the circuit has increased, it is nevertheless divided between the two bulbs which is, as Heather poses, not enough to cause the bulbs to glow.

This line of reasoning occurs later in the program as well. Heather remains uncertain as to why bulbs B and C are not lit since there is more current in the circuit. Her difficulty may arise due to her tendency to use local reasoning which interferes with understanding how the current flows through the entire circuit and, more specifically, through the junctions of parallel branches.

**Analogy Use and Misuse**

The following transcript excerpts (next page) are examples of how the subjects used and misused analogies in their attempts to make sense of the information:
If all moving people must pass through both gates, one after the other, then the rate of flow should be lower. It takes longer for the people to pass through two gates compared to one. Does this seem like a reasonable explanation for the current passing through the two bulbs? Explain.

![Diagram of electrical circuit with two bulbs]

**Transcript**

| D: Yeah, everybody’s got to get single file to get through the one, get single file again to get through the second.  |
| H: But, what if the gates were close enough together, the analogy wouldn’t work, though because once people are in single file here you would go in single file there just as fast.  |
| D: But then you could only continue in single file through the whole rest. These people would eventually catch up to those people.  |
| H: So they obviously have to do it in the middle.  |
| D: Yeah, that’s where it confuses me too, I think.  |
| R: *No analogy is perfect.*  |
| D: uhm hum.  |
| H: But it makes sense why they’re the same brightness, cause here they’re single file and there they’re single file.  |
| D: Yes, they’re going through both at the same rate.  |

**Analysis**

Subject may believe that the track is not packed with people; that is, the wires are not “filled” with electrons.
H: So they're all just staying on one little, they're going through at the same rate.
D: So basically the first one can control the flow.
H: Yeah
D: The second one can only further reduce it. OK

The next circuit had a total of three bulbs in series. How does the brightness of bulb A in this circuit compare to its brightness when it was in the single-bulb circuit? Considering the moving-crowd analogy, how can you account for this result.

![Circuit Diagram]

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: It's the same thing, once they go through A single file, they just go through B single file and C single file.</td>
<td>Recognizes that the track is filled with people.</td>
</tr>
<tr>
<td>D: Uhm hum</td>
<td></td>
</tr>
<tr>
<td>H: What if the resistances are different, though? What if in A you can go though two at a time but B you can only go through one at a time?</td>
<td></td>
</tr>
<tr>
<td>D: Actually, that's not true though, cause the whole thing is full.</td>
<td></td>
</tr>
<tr>
<td>H: But they have to slow down.</td>
<td></td>
</tr>
</tbody>
</table>
D: As they come through gate A, they're going to come into a filled area.
H: And they're going to spread out again?
D: They can't, they're not necessarily going to spread out but it's already full, it's spread out, you know what I mean? Cause the whole circuit, like if it's pressurized, it's all full. So everything is coming into one, then its opening back up. It's not necessarily a single file line of people spreading out.
H: Oooh
D: They're going into another area that's full already. You know what I mean? That's what I was kinda of thinking of.
H: Oh, that makes sense, then cause it's all full, yeah.
D: Know what I mean? So there's all these people full in there and they're trying to be forced through this one little hole. Then the second space is already full as well. So I was thinking the same way you were: Why wouldn't it just be single file the first erh, the first, I guess that's the first resistance doesn't control....
H: Yeah, I was thinking there was this big crowd starting at the top, instead of a whole crowd going through the whole thing at the same time.
D: Yeah
H: What if the resistance is different? What if two people go through B instead of one? [pause]
D: Uhm, it won't be slowed down quite as much [tentatively].
Session 4: Exploring Current Behavior Quantitatively

Tutorial Objectives

The focus of this session was to reinforce the conceptions of current conservation and dependency on circuit configuration (see appendix F for concept map). Using an ammeter, subjects explored current flow quantitatively. Direct quantitative evidence that current is conserved and depends on the total resistance of the circuit was available. The concept of nodes was introduced to formally present the principle of conservation of current. Subjects continued to investigate parallel circuits including independent and dependent branches and current flow at the junctions.

A more quantitative understanding of the relationship between current flow and series resistance (e.g., two bulbs, twice the resistance, half the current) was provided. Although the subjects were not expected to derive the formal equation for the direct relationship between current and parallel resistances (e.g., \(1/R_T = 1/R_1 + 1/R_2 + \ldots\)), it was explored in a qualitative manner (e.g., more bulbs, less resistance, more current).

Overview of Results

The conception of current dependent on the configuration of the circuit continued to strengthen; however, the subjects continued to use their (now
weaker) misconception of current independent of configuration. See appendix L for the concept map. Subjects continued to use the conflicting ideas of current conserved/consumed, although a slight strengthening of conservation conception was evident. They continued to view the battery as the source of current. Their alternate model of why a bulb glows was revised by attributing the bulb's resistance as a function of the current (more current, more resistance, therefore brighter bulb). Although in previous sessions the subjects did not confuse the terms current and voltage, in this session they did.

Although understanding of parallel and series resistances improved, they continued to rely on mechanistic reasoning to explain and predict circuit behavior. The subjects continued to have difficulty in setting up circuits with parallel elements. Subjects did demonstrate an understanding of dependent and independent parallel branches.

**Conceptual Development**

During this session, the subjects used an ammeter to measure the current at different points in series and parallel circuits. They were provided with concrete evidence that current is conserved in both types of circuits. In series circuits, they found that the current remained constant throughout the circuit. In parallel circuits, they found that the total current flowing through the battery was split between the parallel branches. The amount in each branch added together to equal the total current flowing through the battery. However, they continued to demonstrate difficulty in understanding current flow through a parallel circuit. Summarizing what they learned from this session concerning the difference between series and parallel, the subjects provided the following protocol concerning the circuit shown on the next page:
<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
</table>
| H: We know the difference between series and parallel.  
D: Uhm hum  
H: So if we have [pause]  
D: Two resistors in parallel, if they’re equal, will cut double the current.  
H: So if this [A] is 100, then this [B] is 50, and this [C] is 50. But if its [pause]  
D: But two in parallel would each allow 100.  
H: This [F] would be 100, and this [G] would be 100. Right? [pause]  
D: Yes.  
H: If you had 100 going across [E], then [TCH] that would be 100 each [F and G].  
D: Actually, two in parallel will allow twice as much as one, not even two in series, just one.  
H: But they’re still, if you have 100 coming from here [E], they’re still going to get 100 each [F and G].  
D: But you can have 200 coming from there and  
H: Then they’ll have 200 each.  
D: No, they’ll have 100 each. | One of the results they obtained during the session.  
Describing the series circuit.  
Not understanding that the current divides between F and G.  
Don seems to understanding that the current splits, but |
H: No, because they're in parallel, they get the same. Heather does not.

Following this dialogue, Heather states that she gets "voltage and current confused" and writes down the equations that describe current flow in each of the circuits:

- **Series:** \[ I_T = I_1 = I_2 = I_3 = ... \]
- **Parallel:** \[ I_T = I_1 + I_2 + I_3 + ... \]

However, it was very difficult for both subjects to abandon the idea that current is consumed. Using the equations to manipulate arbitrarily chosen numbers and observing the bulb brightness was insufficient to promote conceptual change. Only after the researcher continued to point out discrepancies in their thinking by asking them if bulb brightness was consistent with what they were articulating, did the subjects begin to recognize what was happening in the two circuits. Heather states "So I total equals I1, I2, I3 and on in series. In parallel, I total equals I1 plus I2 plus I3. OK. That makes sense, cause you can see it split right there, but it never splits here. I don't know why I didn't see that before." Although it appears that the conception of current being consumed was changed at this point, the conception continues to be evident during the fifth and final session.

Parallel connections continued to provide difficulty for the subjects. In the next passage, the subjects attempt to predict and explain the behavior of two parallel branches that are in series with each other, as shown below. Although the subjects are able to consider the relative resistances of each branch, they fail to recognize that the two branches have different resistances. Their use of local
reasoning is a contributor to their difficulty in understanding and ability to accurately predict the behavior of a combination circuit like the one shown below.

![Circuit Diagrams]

**Transcript**

<table>
<thead>
<tr>
<th>H:</th>
<th>Well, you know A will be full brightness.</th>
</tr>
</thead>
<tbody>
<tr>
<td>D:</td>
<td>Set up each?</td>
</tr>
<tr>
<td>R:</td>
<td>No just do circuit 2, you did circuit 1 last time.</td>
</tr>
<tr>
<td>D:</td>
<td>OK,</td>
</tr>
<tr>
<td>H:</td>
<td>Review circuit 1. A is full brightness, are they all the same? No, C, D, and E won’t be the same.</td>
</tr>
<tr>
<td>D:</td>
<td>Right. A is full brightness. B and C are half as bright.</td>
</tr>
<tr>
<td>H:</td>
<td>Half and those [D, E, F] are one third...</td>
</tr>
<tr>
<td>D:</td>
<td>So, since they’re in series, each group will get half.</td>
</tr>
<tr>
<td>H:</td>
<td>And then A and B will be half as bright, and C, D, and E will be a third. [pause]</td>
</tr>
<tr>
<td>R:</td>
<td>So... [pause]</td>
</tr>
<tr>
<td>D:</td>
<td>No, A and B are parallel.</td>
</tr>
<tr>
<td>H:</td>
<td>True, they’ll be the same,</td>
</tr>
<tr>
<td>D:</td>
<td>So they’ll each get half</td>
</tr>
</tbody>
</table>

**Analysis**

Referring to bulb A in circuit 1, and comparing bulbs B and C of circuit 1 with bulbs C, D, and E of circuit 2.

Describing circuit 1 correctly; bulb brightness are: $A > B = C > D = E = F$.

Now referring to circuit #2.

Local Reasoning: considering each branch separately but not considering the total resistance of the circuit and hence, the total current flow.
| H: They’ll each get half, and C, D, and E will be...  |
| D: They’ll be half as bright as an individual, |
| H: So C, D, and E will each get half, cause they’re in parallel too. |
| D: But there’s three. |
| H: But they’re in parallel. |
| D: But they have to share half the current. The three bulbs have to share half the current. |
| H: True. [pause] |
| R: So A will be brighter or dimmer than C? |
| D/H: A will be brighter/Brighter. |
| H: Right, A will be brighter. |

At the end of the session, the subjects were asked to review what they had learned. Don’s response centered on realizing that the amount of current through a branch was dependent on the resistance of that branch, specifically whether the bulbs are connected in series or in parallel.

**Reasoning Patterns**

With the familiarity of the equations, the subjects tended to rely on mechanistic reasoning more and more. Even when reviewing information from the previous session, the subjects referred back to the events in their physics class, which emphasized formulae, instead of thinking about to their personal experiences during the sessions (transcript on next page):

| Let’s review some of the things you found out in session three: |
| 1) The current through a battery is not constant but depends on the total resistance of the circuit. |
| 2) The total resistance of the circuit depends on how the bulbs are connected. |

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: Now we have to recall all this stuff.</td>
<td></td>
</tr>
</tbody>
</table>
H: Whether they’re parallel or in series.
D: I drew blank in class
H: Yeah, we did parallel today in class
D: Yeah, I drew a blank when he did current. With parallel
H: Well, you add the I’s
D: With parallel circuit and current
H: V’s are the same, you add the I’s
D: V’s are the same and you add the I’s [laughing]
H: But over here, I’s are the same and you add the V’s, on series.

That is, \( I_T = I_1 + I_2 + ... \) and

\( V_T = V_1 = V_2 = ... \)

and

\( I_T = I_1 = I_2 = ... \)

\( V_T = V_1 + V_2 + ... \)

Even though the subjects tended to rely on mechanistic reasoning, there was evidence of both local reasoning and holistic reasoning. Continuing to work with circuit #2 from above, the subjects were asked to predict how the brightness of bulbs A and B changed if one of the bulbs C, D, or E was unscrewed. Their first responses are typical of local reasoning; however, Don begins to view the circuit more holistically:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: A and B won’t change.</td>
<td>Local Reasoning: Not recognizing that removing one of the bulbs will change</td>
</tr>
<tr>
<td>H: Neither will C and D.</td>
<td></td>
</tr>
</tbody>
</table>
the total resistance of the circuit and hence the amount of current.

Clarifying Question.

Although the reference to "the whole thing" may be construed as holistic reasoning, she is more likely applying what is happening to one group of bulbs to the other group, rather than what is happening to the total resistance and current of the circuit.

Don does recognize that the resistance of the circuit will change ...

... which will affect the total current flowing through the circuit. With bulb C removed, all bulbs will be the same brightness.

After setting up the circuit to test their prediction, the subjects are asked to explain what is happening when the one bulb is removed. Note the reference to the teeming-crowd analogy (next page):
<table>
<thead>
<tr>
<th>Transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: So now, why, A and B drops so that C and D, A and B drops and C and D increases.</td>
</tr>
<tr>
<td>D: They’ll [C &amp; D] brighten and they’ll [A &amp; B] decrease.</td>
</tr>
<tr>
<td>H: Why?</td>
</tr>
<tr>
<td>D: Actually, will they all?</td>
</tr>
<tr>
<td>H: A and B decrease, C and D increase.</td>
</tr>
<tr>
<td>D: But the total current will be less.</td>
</tr>
<tr>
<td>H: Yes, cause there’s less resistance. No, current will be more.</td>
</tr>
<tr>
<td>D: Total current will be less, cause there’s more resistance</td>
</tr>
<tr>
<td>H: Yeah, that’s true, cause there’s more resistance.</td>
</tr>
<tr>
<td>D: Fewer pathways.</td>
</tr>
<tr>
<td>H: But why?</td>
</tr>
<tr>
<td>D: Is that what happens?</td>
</tr>
<tr>
<td>H: Yes, why?</td>
</tr>
<tr>
<td>D: Cause there’s more resistance.</td>
</tr>
<tr>
<td>H: That’s why A and B dropped? I understand why C and D increased, but why did A and B drop?</td>
</tr>
<tr>
<td>D: Oh, cause there is less current.</td>
</tr>
<tr>
<td>H: Oh, yeah. [tentatively]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holistic Reasoning: recognizing that the total current of the circuit will change as the resistance of that circuit changes.</td>
</tr>
<tr>
<td>Reference to teeming-crowd analogy.</td>
</tr>
<tr>
<td>Heather continues to use local reasoning.</td>
</tr>
</tbody>
</table>
D: But actually if there’s, [pause] well I guess there’s less current but its distributed between two bulbs, C and D or C and E. [pause]
R: You are really looking at two things. You are looking at overall current and current through the branches.
H: So these decrease.
D: They’re now all four equal.
H: Uhm hum, I knew they would be equal.
D: Uhm hum. But the overall current is less. The overall current is less, so A and B drop since they’re getting half of it and C, D, and E are getting half of the current but, uhm...
H: Which was more than what they were getting before.
D: Oh, they’re still getting half, they’re getting half of less [laughing]
H: They’re getting more current than they were before...
D: Yeah
H: ... even though its not as much as A and B
D: The grouping is getting half. It’s like they’re getting half of a smaller total.
H: OK, continue.

At this point, the researcher was concerned that the reasoning would shift back to local. However, based on the remaining interaction, the subjects did not appear to attend to the information presented.

Even though all three bulbs of the original circuit were mentioned, the subjects were referring to the modified 4-bulb circuit.

Even though the subjects, especially Don, appears to be developing a more holistic view of electric circuits, when presented with a new situation they relied on local reasoning. The next circuit also provides a disequilibrating opportunity to challenge the subjects to consider how the whole circuit is being affected when a change is made in one part. First, the subjects were asked to predict the relative brightness of the bulbs, and then to build the circuit to test their predictions (next page):
<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
</table>
| D: A and B should be equal.  
H: Equal. | Local Reasoning: This prediction is incorrect and does not take into account the different resistance of the BDE branch. B > A  
B will be greater than D. |
| D: B and D, B should be twice as bright  
H: D will be half as bright.  
D: Yeah  
H: D will be half of B  
H: They’ll [A and C] be the same.  
D: Equal.  
H: Continue  
R: Could you explain why?  
H: The brightness of A and C?  
R: About the whole thing.  
D: The brightness of B compares to the brightness of D? Should be twice as bright cause they each get half, this group, if that, that can represent a multiple, and that gets half and half.  
H: Yeah. | Correct prediction, A = C |

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After setting up the circuit, the subjects are surprised to find that bulb B is brighter than bulb A. They failed to understand that the parallel branch containing bulbs D and E has a lower resistance than bulb C in the AC series branch. Lower resistance means more current through the BDE branch, and since bulb B receives the full current, bulb B will be brighter than bulb A. Here's how the subjects responded:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: Ohh, we were wrong. B's brighter than A. Oh, you know why? D: Oh, there's less resist, uhm. H: Oh, I don't know why. There's less resistance in parallel. D: There's less resistance through that side. That's right. So we were wrong. H: So two bulbs in parallel is still less resistance than one bulb in series. D: uhm? H: D and E are less resistance than C. Two bulbs in parallel is less resistant than one bulb in series. D: That's right.</td>
<td>Local reasoning, although the focus is now on branches instead of individual bulbs.</td>
</tr>
</tbody>
</table>

Once they observed the actual brightness of the bulbs, they were able to explain the results accurately. However, Heather continues to have difficulty with current flow through a parallel circuit (next page):
### Transcript

| H: Then why are those not even hardly lit? Cause they get half?  
D: Uhm hum.  
H: But you would think they [D and E] would be this bright [A or C]. Cause you would think it would be like half of this. You know? And they're like not even, [pause], see, these two [D and E] are less than these two [A and C]. But there's less resistance here than here.  
D: There's less resistance overall.  
H: Then why are these two less than these two? Cause of that one [B]? | Analysis  
Local Reasoning: The focus remains on certain parts of the circuit -- what is occurring at each bulb -- instead of examining how the current is flowing through the entire circuit. |

At this point, Heather provided Don with an interesting alternative explanation as to why bulbs D and E are less bright than bulbs A and C. Although her explanation is based on the misconception of bulb B consuming the current and uses sequential reasoning (bulb B is before bulbs D and E), Don nonetheless gives it serious consideration. After a lengthy pause, Heather reposes her query:

### Transcript

| H: Cause this [B] takes half of what they did [D and E]? Oh, this [B] takes half of what these [D and E] did, where these [A and C] get half each.  
D: Uhm hum.  
H: So these [D and E] get a sixth. No. | 

The researcher is not certain how Heather arrived at the conclusion that D and E would receive one-sixth the current. However, if you consider the current splitting at the junction of A and B (that is, the junction “taking” a fraction of the
current), and A and C each take a fraction, B takes a fraction, and D and E each take a fraction, then that would be a sixth each. At this point, the subjects could not proceed and the researcher intervened:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R:</strong> Compare the current flowing through A/C and the current flowing through B. Is the current the same, less, or greater in A than B?</td>
<td>Although recognizing that the branch containing BDE receives more current because it has a lower overall resistance, Don implies that half the current is consumed by bulb B. Clarifying Question.</td>
</tr>
<tr>
<td><strong>D:</strong> Since there’s more current, this is getting half...</td>
<td><strong>R:</strong> Why is B getting, say that again.</td>
</tr>
<tr>
<td><strong>H:</strong> There’s less, well they’re each getting the same...</td>
<td><strong>D:</strong> B is getting half of a greater amount of current. Since there is more current going through that branch, since overall there’s less resistance. Not necessarily half but...</td>
</tr>
<tr>
<td><strong>D:</strong> this is getting half of its own.</td>
<td><strong>R:</strong> Half compared to what?</td>
</tr>
<tr>
<td><strong>H:</strong> But this one’s getting more because there’s less resistance here.</td>
<td><strong>H:</strong> A and C.</td>
</tr>
<tr>
<td><strong>D:</strong> Uhm hum, there’s more current going through this branch because there’s less resistance and B is getting half of that current, half of a greater amount of current.</td>
<td><strong>D:</strong> A and C should get half of their...</td>
</tr>
<tr>
<td><strong>R:</strong> Why is B getting, say that again.</td>
<td><strong>H:</strong> No, A and C get a full and B, D, and E get a full.</td>
</tr>
<tr>
<td><strong>D:</strong> Uhm?</td>
<td><strong>D:</strong> Uhm?</td>
</tr>
<tr>
<td><strong>H:</strong> Each are getting the same thing because they’re in parallel. So each one of these is getting the same.</td>
<td><strong>H:</strong> Each are getting the same thing because they’re in parallel. So each one of these is getting the same.</td>
</tr>
<tr>
<td><strong>D:</strong> No, I’m saying that A and C each get half of the current in their branch.</td>
<td><strong>H:</strong> Each are getting the same thing because they’re in parallel. So each one of these is getting the same. Implies current is consumed.</td>
</tr>
</tbody>
</table>

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H: Right, and then B gets, yeah, more than half because there's more... less resistance. That doesn't make sense. [pause] no.

The subjects continued with this line of reasoning, focusing on something being consumed and the role of resistance in that process. As a result, they developed an alternative model for why the bulb's brightness changes -- a model based on the resistance of the bulb changing instead of the current changing due to the total resistance of the circuit changing. The next excerpt follows the development of their alternative model:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: So if it's less resistances why is B so bright, and D and E not barely anything? If it was less resistance you would think that D and E would be more bright than C, cause its less resistance, more stuff flows through. You know?</td>
<td>Local Reasoning: Failure to recognize what is occurring at the junctions of the parallel branch.</td>
</tr>
<tr>
<td>D: Less resistance, more stuff, but it requires resistance to make the light light.</td>
<td>Don takes the idea of resistance being necessary for the bulb to light as the starting point.</td>
</tr>
<tr>
<td>H: Why does B get all of it?</td>
<td></td>
</tr>
<tr>
<td>D: Something is consuming the current.</td>
<td></td>
</tr>
<tr>
<td>H: Yeah, that's what you would think.</td>
<td></td>
</tr>
<tr>
<td>R: Think about the moving-crowd analogy.</td>
<td></td>
</tr>
<tr>
<td>D: I think we're kinda think backwards. It takes resistance to make the light light. If there's too little resistance, you won't have light.</td>
<td></td>
</tr>
<tr>
<td>H: Oh, yeah, that's true. Cause I keep thinking less resistance, brighter bulb.</td>
<td>Which is true: less resistance means more current, and more current means a brighter bulb.</td>
</tr>
</tbody>
</table>
D: Yeah, less resistance, more current, but if there’s not enough resistance there won’t be...
H: there won’t be a, it won’t...
D: ... the bulb won’t light. There’s not enough current.
D: So that’s [B] taking up enough of the current that these aren’t getting enough to light?

After this point, the subjects continued to work through the apparent discrepancy of bulbs D and E being much dimmer than the other bulbs. The subjects relied more and more on mechanical reasoning to explain the behavior of this circuit:

<table>
<thead>
<tr>
<th>Transcript</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H: A and C are in series, so they’re getting half,</td>
<td>100 amps through branch AC with each bulb getting half, i.e., current consumed, but he does recognize more current will be going through BDE branch which has a lower resistance.</td>
</tr>
<tr>
<td>D: So if there is 100 amps, these would each be getting maybe 50, running through this branch, but there would be more than 100 running through that side because there’s less resistance.</td>
<td>Local Reasoning</td>
</tr>
<tr>
<td>H: No, 100 goes through each because they’re in parallel.</td>
<td></td>
</tr>
<tr>
<td>D: So let’s say you have 100 amps going through A/C...</td>
<td></td>
</tr>
<tr>
<td>H: You would have 100 amps going through B/D/E.</td>
<td></td>
</tr>
<tr>
<td>D: No you would have more going through B/D/E because there’s less resistance.</td>
<td></td>
</tr>
<tr>
<td>H: But if it’s in parallel, the same amount goes through each side. If you have 120 here, you have 120 here.</td>
<td></td>
</tr>
</tbody>
</table>
D: So this, I would think this [B] would be getting 60 and these [D and E] would each be getting 30, since they're all the same, no because it's one over the, not, without actually figuring it out, it's the one over the resistance and that kinda of stuff.
H: Yeah, right. I still think D and E would be half as bright as B. But B is like really bright and those two are really dim.
D: Uhm hum.
H: Unless, like you said, there's not enough resistance
D: Cause if these are getting basically half of half, you know what I mean, they're getting half the current through here but its split through two, so these would each be getting half of 100, say 50, but these would each be getting a fourth of 120, which would be like 40, so that's why they're more dim than, that's why they're dimmer than A and C, but I don't understand why they don't light at all.
H: Because they're getting 30 and these ...
D: I don't know if that's it or not, I just picked numbers.
H: ... 60. So it would be half as bright.
D: Unless that's not enough to light them at all. But as bright as that is, compared to the other bulbs we've seen, I would think it would still light.
H: It makes sense if you do it as in this gets 100 and this gets 100, so this will get 50 and these will get 25, half of that, and D and E would get half of 50.

Mechanical Reasoning: trying to remember the equation for equivalent resistance in a parallel circuit.

Returning to the alternative model.

Mechanical Reasoning: Choosing arbitrary numbers to manipulate in order to describe or explain circuit behavior.
The other subjects presented alternative models very similar to this one.

**Analogy Use and Misuse**

The subjects made only two references to the teeming-crowd analogy (referring to paths or pathways in the circuit) and no references to the water analogy. However, without being solicited, they did make the following statements at the end of the session:

**Transcript**

D: The water analogy helps. Like when I’m thinking about the parallel circuits, cause you can think of double the water can travel through two pathways but if they’re both in series, you’re basically limited by the first one. If the second resistor is equal, it’s not going to lower the current.

H: The people one helped too. The people one I liked because if its more resistance, then it’s less people can get through, because it’s smaller.

**Session 5: Introduction to Potential Energy and The Battery**

**Tutorial Objectives**

This session focused on the role of the battery, electric potential energy, potential difference, and voltage. Specifically, the function of the battery is to provide energy to the circuit and to propel the electrons through the circuit. Electric potential energy was presented via the analogy of gravitational potential energy associated with a ball held above the ground. Potential difference was introduced by having the subjects quantitatively measuring the potential at various points throughout the circuit and having the subjects calculate the difference in potential across a bulb, a resistor, and a battery. This value was then compared to the voltage across each element as measured by the voltmeter. The concepts of emf was presented. The battery as a constant voltage source was investigated through several inquiry activities. The internal functioning of the battery was explained by the conveyor-belt analogy. The concept map for this
session is found in appendix G. This map also represents the “expert” map based on the concepts and relations as presented in the instructional program.

Overview of Results

As indicated by the concept map in appendix M, the subjects continued to use several misconceptions: Current independent on bulb configuration, current consumed, the battery as the source of the current, and the bulb’s resistance as a function of the current. However, the concept of conservation of current was strengthened as was the conception of the current dependent on total resistance of the circuit.

The role of the battery, electric potential energy, and potential difference were only weakly developed. The subjects viewed the concept of voltage in terms of it being “the opposite of current.” (This conception stems from mechanical reasoning.) Predominate reasoning patterns continued to be mechanistic and local/sequential. Some holistic reasoning was evident.

Conceptual Development

The relationship between current in a circuit and the total resistance of that circuit continued to be elusive to the subjects. Part of their difficulty may be attributed to the predominate use of local and mechanistic reasoning and the misconception of current being consumed by the bulbs. In this session, the subjects continued to explore combination circuits which contained bulbs in parallel and in series. With the definition of a node and the formal definition of conservation of current, the subjects were asked to compare the current flow at each of the points in the circuit on the next page:
D: 1 and 7 equal ...
H: and the greatest. And, would 3 and 2 be equal? It splits here but will A have anything to do with current? No. So 2 and 3 ...
D: Actually, no, cause current through this whole branch [BDE] will be greater than this branch. Remember? Less resistance. So 3 would have to be greater than 2. 3 will equal 6.
H: Yeah, 3 is equal to 6, which is less than 1 and 7.
D: Right, which is less than 1 and 7.
H: 4 and 5 are equal. And 4 and 5 will be less or greater than 2?
D: Half of [pause]
H: Less.
D: Yeah, less than 2. Half of 3 and 6.
H: 4 and 5? Yeah, half of 3 and 6 and less than 2. Cause if 3 was 100, 4 and 5 would be 50. But 2 would be....
D: Yeah, less than 2. 2 is just less than 3, right?

Correct.
Local Reasoning: focusing on influence of A instead of resistance of branch.

More holistic, considering resistances of each branch.

3 is greater than 2 and equal to 6.

Correct.

4 and 5 are equal.

This mechanistic reasoning, based on the arbitrary assignment of numbers, can hinder students' understanding. Students do not know how the current will divide because they do not have specific values for the bulb's resistance.
H: OK, if one's 100, aren't all resistances equal? Is three 50?
D: Uhm, no, it would be little greater than 50.
H: Oh yeah, because of all this [referring to BDE].
D: Maybe like 60 [for 3] 40 [for 2]
H: That would be 60 and if you put one here it would be 40.
D: So like 60 and 40, so that would mean these [A and C] would get 20...
H: And these [D and E] would get 30 and 30.
D: Or these would be 30 [B], 15 and 15 [D and E].

In this case, they are uncertain as to what values to assign 2 and 3.

So the students, again, arbitrarily assign values which are typically incorrect.

Still implies current consumed.

The subjects were then instructed to describe the current flow at each node. The subjects accurately described the flow through the first node present: 1 > 3 > 2 and 3 + 2 = 1. However, they encountered difficulty with the next two situations:

**Transcript**

H: 4 and 5 is half of 3.
D: 4 and 5, [pause], yeah each half of 3, no each a fourth of 3.

**Analysis**

This is a correct statement.

Incorrect statement.
Bulb B consumes half the current.

H: 4 and 5 is a fourth of 3?
D: No, cause remember each of these is going to get a fourth of this total, B will get a half, each of these will get a fourth.
H: Oh, yeah. cause they’re in [pause] series.
D: "Is current conserved here?" Yes. [TCH] since its point 3 but then it points to this junction, so it’s after B but its still one-third of, or one-fourth, they each get a fourth of what’s flowing through point 3.

The third situation was also viewed from a local perspective and included the misconception of current being consumed, but not being consumed:

**Transcript**

| H: Well, if 6 is equal to 3 then its the same comparison. |
| D: Uhm hum |
| H: They’re [pause] getting half of a half |
| D: Of the total, the total going through 3, B will get half and D and E will each get half, combined, and recombine at 6. |
| H: OK. |

**Analysis**

| Same comparison as 3-4-5 node. |
| Bulb B will consume half, D and E will each get a fourth, but the current recombines at point 6. |
The battery as a constant voltage source was relatively easy to establish. The subjects discovered that for parallel circuits, the voltage is independent of resistance. The voltage across elements in parallel remains constant and equal to the total voltage of the battery. The voltage of the battery is not affected as elements are added to the circuit. Heather explains the situation like this:

"In parallel, each one is basically connected to the battery on its own, but in series they’re not. They’re connected in series, one right after the other. If you wanted to hook that up to the battery, it's the same. See it starts here and goes straight over to the battery, there’s nothing in between. So basically, if anything is in parallel, it’s connected straight to the battery. Whereas if you’re in series, you’re not connected straight to the battery. There’s something between you and the battery, another resistor. So the voltage in here is going to be all the same because they’re basically connected to the battery."

The concepts of potential and potential difference were more difficult to establish. Using the circuit below, the subjects measured the circuit’s potential at several places relative to the negative terminal of the battery. They were asked to compare the potential at each side of the elements and then they calculated the potential difference across each of the circuit elements using the values of potential. Finally, they measured the voltage (potential difference) across the circuit elements and compared the calculated values with the measured values. Their data is next to the circuit shown on the next page.
The subjects observe that potential decreases as you move away from the positive terminal of the battery: Heather explains the situation by saying "Cause you’re going further and further away, and you’re losing potential." From their data, they see that the calculated potential difference across the element is equal, or almost equal, to the measured voltage across the element. When asked to summarize the most important information gained from this session, the subjects describe the difference between current and voltage as being "the opposite. They each behave oppositely in parallel and in series. Like in parallel, current is split between the two branches, voltage is equal. But in series, current is equal in all stages and voltages added up to the total."

Reasoning Patterns

Local/sequential reasoning occurs in several forms, for example, focusing on a particular part of the circuit and the order of the bulbs as the defining characteristic. Another example of local/sequential reasoning occurs when the student believes that the bulb brightness or current amount is dependent on the physical distance of the bulb: The farther away the bulb is from the battery, the less current there will be and therefore the dimmer the bulb. In this case, the
subjects were investigating the brightness of two different bulbs, a pink one and a white one. They were challenged to determine which bulb had the greater resistance based on the bulb brightness (current flow) and the voltage across each bulb. They compared the bulbs in a series circuit and in a parallel circuit, as shown below, and determined that when the two bulbs were in series (that is, equal current flowing through both bulbs), the pink bulb was brighter and had more volts across it (1.25V c/w 0.05V). However, when they were in parallel, the white bulb was brighter and they both had the same voltage (1.3V):

---

**Transcript**

**H:** Less volts go through the white one in series.

**D:** So there's a greater potential across the pink bulb than the white.

**H:** But the pink's further away. No it isn't, it's closer. You hooked this thing up screwy.

**D:** Current. In parallel, they add up to the total. In series, they're equal to the total.

**H:** So which one has the more resistance?

**D:** In series, current [through both bulbs] is equal.

---

**Analysis**

Misspoken: volts do not "go through."

Local Reasoning: Behavior based on its physical distance from the battery.

Mechanistic Reasoning:

\[ I_T = I_1 + I_2 + I_3 + \ldots \]

\[ I_T = I_1 = I_2 = I_3 = \ldots \]
Don made an interesting association between current and voltage which appears to stem from mechanistic reasoning. Formulae-wise, the behavior of current and voltage in series and parallel circuits can be expressed as (next page):
<table>
<thead>
<tr>
<th>Series Circuits</th>
<th>Parallel Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_T = V_1 + V_2 + V_3 + \ldots$</td>
<td>$V_T = V_1 = V_2 = V_3 = \ldots$</td>
</tr>
<tr>
<td>$I_T = I_1 = I_2 = I_3 = \ldots$</td>
<td>$I_T = I_1 + I_2 + I_3 + \ldots$</td>
</tr>
</tbody>
</table>

Using this information, Don develops an association to help him remember how current and voltage can be thought of (emphasis is researcher’s):

“['That should be easy to remember, because in parallel, the current is able to branch, and we know that if the current branches the voltage doesn’t. Know what I mean? Since they’re inversely related.’]

**Analogy Use and Misuse**

To help explain the concept of electric potential energy, the analogy of gravitational potential energy of a ball held above the ground was used. After collecting the values of potential around a circuit, the subjects were asked to explain how the potential changes as you move from the positive terminal of the battery to the negative terminal where the negative lead of the voltmeter was connected. Heather used the gravitational potential energy analogy to help her explain what was happening:

“['It approaches zero. Oh, that makes sense! You’re losing potential. At A you’re going to have the most potential. It’s like the ball, the higher you are the more potential you have. So A has the biggest potential and E don’t have anything cause you’re at the bottom, you’re at ground level.’]

**Post-Instructional Results:**

**Overview**

Although both subjects did not achieve the level of understanding designated by the tutorial session five concept map (appendix G), they did improve their original, naive models of an electric circuit (see appendices N and
O for the post-instructional concept maps). Both developed a complete understanding of the concept of a circuit as a continuous loop with multiple paths through which the current follows a round trip path. Both subjects demonstrated a better understanding of the role of the battery, potential, and potential difference. Heather seem to distinguish between potential and potential difference better than Don. Don, however, abandoned the misconception that current was independent of circuit configuration, whereas Heather continued to apply that concept only to series circuit. Both subjects continued to believe that current was "shared" by bulbs in series, implying a lack of complete development of the concept of conservation of current. Finally, both subjects developed the misconception that the total voltage of a circuit can change (that is, the battery is not a constant voltage source).

Predominate reasoning pattern remained mechanistic. Only Don made reference to one of the analogies, the water-circuit, in explaining his answer.

**Concepts Present**

Even though both subjects were able to correctly predict the brightness of the bulbs shown in the circuits below, they were unable to correctly account for the current amounts and/or flow in the two circuits.
c. How does the current through the battery in circuit I compare to the current through the battery in circuit II? Explain.

<table>
<thead>
<tr>
<th>Subjects' Response</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D: The current through circuit I will be approximately twice the current in C-II [circuit II]. Each bulb in C-II receives equal current (series), therefore, bulb B &amp; C receive half the current.</td>
<td>Although he correctly states that the current amounts will be different (current dependent on configuration), he incorrectly states that each bulb in circuit II will receive (share) the current: implies current is consumed.</td>
</tr>
<tr>
<td>H: I current is the same, thus B and C are half as bright.</td>
<td>Incorrectly believes that current is independent of circuit configuration and consumed.</td>
</tr>
</tbody>
</table>

However, when asked to compare current at specific points within a two-bulb series circuit, the subjects indicated that current was conserved.

A similar situation occurred when the subjects compared a single bulb circuit with a two-bulb parallel circuit. They were able to accurately describe the relative brightness of the three bulbs but had difficulty in explaining the current amounts and flow in each circuit:

---

Battery

Circuit I

Bulb A

Circuit II

Bulb B

Bulb C

---

c. How does the current through the battery in circuit I compare to the current through the battery in circuit II? Explain.
<table>
<thead>
<tr>
<th>Subjects' Response</th>
<th>Analysis</th>
</tr>
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<tbody>
<tr>
<td>D: B-I current is double B-2. B-2 provides equal current to both bulbs.</td>
<td>This explanation is backwards: Circuit 2 provides double the current.</td>
</tr>
<tr>
<td>H: The battery in circuit 2 will have more current to allow the 2 bulbs to have full brightness.</td>
<td>This is a correct explanation, however it is in conflict with her previous explanation on series circuits.</td>
</tr>
</tbody>
</table>

Again, when asked to compare the current at specific points within a two-bulb parallel circuit, they correctly identified the locations where the current would split and recombine with the total flow remaining conserved.

Potential difference tended to be explained using mechanistic reasoning including the use of equations. It was difficult to evaluate their understanding of potential difference beyond their use of technical knowledge. They were both able to demonstrate an understanding of the difference between potential difference in a series circuit and potential difference in a parallel circuit. However, they had previously demonstrated a reliance on the equations describing those two situations (Series: $V_T = V_1 + V_2 + V_3 + ...$; Parallel: $V_T = V_1 = V_2 = V_3 = ...$). However, when asked to compare the potential differences across bulbs in a combination circuit as shown below, their responses were incomplete (next page):
c. Compare the potential differences across each of the bulbs. Explain.

Subjects' Responses

D: The P.D. [potential difference] will be greater through A and D. The parallel section B-C has less R [resistance].
H: Pot. difference goes from high to lower as it moves from A to D.

Question

d. How does the potential difference across the battery compare to the potential difference across each of the bulbs? Explain.

Subjects' Responses

D: The P.D. [potential difference] of the battery will equal the total of the P.D.'s across each section.
H: Pot. difference is less from points 3 -> 4 [across bulb A] as from 1 to 2 [across battery]. 1 to 2 has the most.
Reasoning Patterns

Mechanistic reasoning was clearly evident in their responses to the post-test questions. The first post-test question asked the subjects to write down their ideas that helped them to explain and predict the behaviour of electric circuits. They were also provided with verbal instructions to be as detailed and complete as possible and to write down all ideas without concern for whether their responses would be “right” or “wrong.” Although they had over two-thirds of a page in which to respond, they were also instructed to use the back of the pages as necessary. Both Don and Heather simply wrote the equations for series and parallel circuits:

Series: \[ I_T = I_1 = I_2 = I_3 = \ldots \]
\[ V_T = V_1 = V_2 = V_3 = \ldots \]
\[ R_T = R_1 + R_2 + R_3 + \ldots \]

Parallel: \[ I_T = I_1 + I_2 + I_3 + \ldots \]
\[ V_T = V_1 + V_2 + V_3 + \ldots \]
\[ 1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \ldots \]

Don supplemented his equations by writing “Current like water will follow the path of least R [resistance]. I [current] is equal throughout series circuit while the voltage potential drops at different points.” For the most part, Don seemed to demonstrate a partial understanding of potential and potential difference. He understood that potential decreased from one side of an element to the other side. However, this change in potential was not strongly connected to his conception of potential difference. He did not consistently describe potential difference in correct terms when dealing with parallel circuits.

Heather demonstrated a more consistent understanding of potential and potential difference in series and parallel circuits. She seemed to understand the
connection between potential and potential difference, as indicated by her response to the following question:

Q: How does the potential differences across points 1 and 2 compare to the potential difference across points 2 and 3? Explain your answer:

Subject's Response

H: Your (sic) going from highest potential at point 1 to lowest at point 3. Point 2 will be in the middle. The "difference" is equal. 1>2>3, 1 - 2 = x, 2 - 3 = x, x same value.

Although she seems to understand potential, her understanding of potential difference and its connection to potential is not as firmly established: the quotes are hers.

She has more difficulty comparing and explaining the potential difference across the battery and across one of two bulbs connected in parallel. One problem with mechanistic reasoning is the tendency to arbitrarily assign values; in this case, she assigned an equal resistance to the battery and to the bulb. Inappropriate use of Ohm's law resulted in an incorrect conclusion that the potential difference across the bulb (points 2 & 5) was one-half that across the battery (points 1 & 4), next page:
points 1 & 4

\[
\begin{align*}
U &= ? \\
R &= 1 \\
I &= 100 \\
(100)(1) &= 100 \text{ V}
\end{align*}
\]

points 2 & 5

\[
\begin{align*}
U &= ? \\
R &= 1 \\
I &= 50 \\
(50)(1) &= 50 \text{ V}
\end{align*}
\]

resistance is equal
Chapter 5
DISCUSSION AND IMPLICATIONS

Introduction:

The principal objectives of this study were to identify the: (a) concepts and conceptual relationships that comprise the subjects' mental models; (b) sequence of changes the models undergo; and (c) types of changes the mental models undergo as subjects acquire better understanding. A secondary objective of this study was to examine the reasoning patterns used by the subjects as they struggled to make sense of the concepts and phenomena presented. The types of qualitative reasoning used by the subjects is important because these reasoning patterns influence what they learn (Licht, 1991; Cohen, Eylor, and Ganiel, 1983; Cosgrove, Osborne, and Carr, 1984).

The concepts and conceptual relationships comprising the subjects’ mental models were represented by concept maps (appendices H-O). The sequence and types of changes the models underwent were illustrated by the changes in the conceptual maps as the subjects progressed from a naive understanding towards a more scientific understanding (Dykstra, et al., 1992).

The Process of Conceptual Change:

Conceptual change is described in a number of ways by different researchers: conceptual development, resolution, and exchange (Pines and West, 1986a); accretion, restructuring, and tuning (Norman, 1978); differentiation, class extension, and reconceptualization (Dykstra, et al., 1992); and assimilation and accommodation (Carey, 1985). Each of these theories share similarities in their
description of the process of conceptual change. Each theory is also an incomplete description of the process.

Conceptual change is easiest to describe in the broader terms of assimilation and accommodation (Carey, 1985). Assimilation occurs when new concepts are added to an existing framework. The relationship among the new and existing concepts are rearranged. The concepts themselves are not changed, only their applicability. Assimilation is similar to accretion as defined by Norman (1979), conceptual development as defined by Pines and West (1986a), and differentiation as defined by Dykstra and his colleagues (1992).

Accommodation is the reorganization and elaboration of an existing conceptual framework to accommodate new concepts. This process involves changing conceptions. Similar to conceptual exchange (Pines and West, 1986a), restructuring (Norman, 1978), and class extension and reconceptualisation (Dykstra, et al., 192), accommodation often results in the development of new conceptual frameworks.

Both assimilation and accommodation occurred to different degrees: from the acquisition of a single, simple idea (or separation of a single, minor idea) to the development of elaborate and inter-related ideas. In both cases, the process was not simple nor straight forward. Rather, the process is better described as a painful negotiation and renegotiation of conflicting beliefs. The “path” from naive towards expert understanding goes in both directions, with subjects moving backward (toward personal theories) as easily, if not more so, as forward (toward expert understanding).

Misconceptions are as easily incorporated into the subjects’ frameworks as are scientific conceptions. Conflicting ideas are held concurrently and without
any perceived difficulty. Appropriate frameworks are recreated into less
appropriate frameworks only to be recreated into more appropriate ones. Some
misconceptions are firmly retained despite the empirical evidence to refute them.
Conceptual change -- in this case, learning and reasoning about electric circuits --
can be described as a painful and messy process.

Learning and Reasoning About Electric Circuits:

Sections of the concept maps are presented in more detail to illustrate
conceptual change as a process of assimilation and accommodation. Although
this description does have limitations in that it will not describe all changes, it is
a useful way of illustrating how some of the changes occur. Figure 16, next page,
illustrates the process of assimilation of the framework associated with the
conception of a complete circuit. In this case, the framework is expanded as the
conception is elaborated to include the ideas of open and closed, conductors and
insulators, etc. In this case, the change is evident by comparing the naive map
with the first transitional map.
Figure 16 - Example of Assimilation

Figure 17, next page, illustrates the process of assimilation within the same framework. Here, a smaller unit of the framework (instead of the primary framework) is expanded. In this case, the concept of a continuous loop is elaborated to include the structures of the bulb and battery, as evident on the first transitional map. Note how the misconception of the battery as the source of electrons/current was also assimilated.
Figure 17 - Assimilation within The Circuit Framework on Map 1.

Figure 18, next page, illustrates the process of assimilation of concepts associated with current. The transition is from session one (map 1) to session 2 (map 2). The concept of current is more elaborate and includes the misconception of current independent of circuit configuration. Note how the misconception of current being consumed is retained. This misconception was present as part of the subjects’ naive model and was held throughout the study.
Figure 18 - Assimilation of Concepts Associated with Current, Map 1 to Map 2

Figure 19, next page, illustrates the continued process of assimilation of concepts associated with current. In this case, change is occurring from transitional map two to map three. The concepts of series and parallel are becoming better defined. The misconception of current consumed was first challenged during session two and it is in direct conflict with the correct conception of current conserved. The subjects were able to maintain and use both conflicting models throughout the study. Note also the appearance of mechanical reasoning, with the inclusion of equations describing circuit behavior. Immediately upon receiving the equations in their physics class, the subjects incorporated them into their model without developing a qualitative understanding of what they represent. The reliance on the equations and using
mechanical reasoning interfered with the development of conceptual understanding and, hence, the process of conceptual change. Instead of attempting to understand why something was happening, they would test each equation to determine which would work. Once that was determined, the subjects believed that they understood what was happening.

Figure 19 - Assimilation within the "current dependent on configuration” Framework

The changes that occurred during session four can best be described in terms of tuning (Norman, 1979). Although the subjects are acquiring new concepts, the predominate process was a refinement of their existing knowledge structures. This refinement is noticeable by comparing map three, a more complex map, to map four. However, several changes to the framework for current are evident; for example, the concept of dependent parallel branches was
added. One interesting change involved the concept of "voltage," originally separate in concept maps two and three. In map four, the concept of "voltage" was subsumed into the concept of "current" (see Figure 20, next page).

![Figure 20 - Inappropriate Assimilation of Concept of "Voltage"

Although the subjects inappropriately assimilated "voltage" with "current" during session four, session five provided the experiences necessary for accommodation and additional assimilation to reverse their previous belief. Figure 21, next page, illustrates the restructuring of the "current/voltage" framework from map four into the two separate frameworks of "current" and "voltage," as shown in map five. The "voltage" framework also illustrates the assimilation of additional concepts.
Accommodation was also evident by changes that occurred between the naive map and the first transitional map, again, with concepts associated with current and voltage (Figure 22, next page). The naive framework was restructured into two separate frameworks, one for current and one for voltage. The framework for current was then elaborated through the process of assimilation. As indicated earlier, the two separate frameworks were later recombined (map 4) only to be restructured again (map 5).
The changes illustrated in figures 20 through 22 illustrate the complexity of conceptual change: Ideas and beliefs that are accurate and scientifically appropriate are not necessarily firmly held by students. The subjects began with an inaccurate personal belief (naive map - voltage and current the same) that was changed to a more scientifically accurate belief (map 1 - voltage and current different). The new belief was abandoned for the original belief (map 4 - current and voltage the same), but through additional experiences, acquired a more complete and accurate understanding (map 5).

Accommodation and assimilation can occur in both directions: acquiring and restructuring beliefs to produce a more scientifically sound model or a less
scientifically sound model. There is no assurance that once an idea or conception is integrated into an existing framework, or a new framework created to accommodate the conception, that the change is permanent. In fact, throughout this study, subjects’ models continually flip-flopped between naive misconceptions to scientifically sound conceptions to return to their original beliefs. However, remarkable conceptual change did occur during this study.

A comparison of Heather’s naive map to her post-instructional map illustrates the degrees and types of conceptual change. Assimilation is clearly represented by the elaboration of the concept of a circuit (figure 23).

![Diagram showing assimilation from naive to post-instructional map]

Figure 23 - Assimilation from Naive to Post-Instructional Map
Accommodation and assimilation are evident by examining the changes in the conceptual frameworks for current and voltage. Several misconceptions, in conflict with the scientific conceptions also present, were retained (see figure 24, next page). Note also the influence of mechanical reasoning.
Throughout the study, several issues were evident. First, it was apparent that personal models or beliefs hindered the conceptual change process by
influencing what information they attended to. As described by Duit (1991a), what the student attends to is influenced by what they already know. Their personal beliefs were strongly held even in the presence of conflicting empirical evidence. The personal beliefs of current being consumed and current independent of circuit configuration remained as part of the subjects’ models of electric circuits.

In several instances, rather than abandon their personal model, the subject would devise an alternate model to explain the situation but allow them to retain their personal models; for example, postulating that the bulb’s resistance is a function of the current to explain why the bulb can change brightness, or that “something else [other than current] must be dividing” to support their model of current independent of circuit configuration (session 2).

In this manner, the subjects could explain the empirical evidence without abandoning their personal models. Empirical evidence was not always enough to change the subjects’ personal conceptions (Duit, 1991a; Glynn, Yeany, & Britton, 1991). Collecting quantitative data on current amounts within circuits did not always result in the development of the conception of current conservation. Comparing the brightness of bulbs in different circuits did not adequately challenge their personal conception that current remains constant, or independent of circuit configuration.

A second issue is related to the issue of prior knowledge. Students are able to maintain and use conflicting models. As Pines (1985) found, the subjects easily maintained and used conflicting ideas to explain circuit behavior (session 3). One subject used the idea of current conservation to explain parallel circuits and current consumption to explain series circuits (post-test). In this case, the
subject had one model to explain one situation and the second model to explain
another situation. This type of model use is related to the third issue, the effect of
reasoning patterns.

Third, the type of reasoning pattern used by the subjects influenced the
conceptual change process. As in the case described above, local/sequential
reasoning hindered the subjects in developing the conception of current
dependency on circuit configuration. The subjects tended to focus on specific
points on the circuit without considering the entire circuit: Series and parallel
connections within the same circuit were viewed separately. Local reasoning
also hindered the subjects’ understanding of current flow through parallel
circuits (sessions 3 and 4). Local reasoning also hindered the formation of the
concept of current conservation. The subjects focused predominately on what
was happening at each bulb in the circuit, instead of the current flow through the
entire circuit.

Mechanistic/technical reasoning also hinder the development of
understanding. Subjects readily resorted to equations and technical (recall)
knowledge to explain circuit behavior (sessions 3-5). Not only was using
equations to manipulate arbitrarily chosen numbers insufficient to promote
conceptual change, this mode of explanation prevented qualitative
understanding from developing. This effect of mechanical reasoning is
consistent with results obtained by Williams, Hollan, and Stevens (1985).

Teaching Concepts Associated with Electric Circuits:

Constructivist learning and teaching theory is, in part, concerned with
students constructing knowledge from personal experience and through social
interaction. This study supports several tenants of constructivist theory: (1) prior
knowledge needs to be addressed; (2) students need to be involved in active construction of understanding; and (3) social interaction promotes conceptual change.

Personal knowledge influences learning (Glynn, Yeany, & Britton, 1991). A student’s ability to selectively attended to information based on personal theories or experiences is one factor that makes conceptual change teaching a challenge and emphasizes the need to consider students’ prior knowledge during instruction. This was evident throughout the study and clearly prevalent during session two.

Developing conceptual understanding requires constructing knowledge through inquiry and application. The subjects were able to significantly change their naive models of electric circuits through an instructional program that was based on a learning cycle of exploration/invention/application (Karplus, 1980). The exploration portion used disequilibrating experiences to challenge the subjects’ current understanding. The invention and application portions provided hands-on, inquiry-based activities to promote conceptual change. Analogies assisted some of the learning but not all, for all subjects. Finally, the subjects were able to explore the same conceptions in a variety of contexts over a period of time.

Social interaction promotes conceptual change (Champagne and Bunce, 1991): Peer dialogue enhanced the conceptual change process by allowing the subjects to explore and challenge ideas in a less threatening setting. Subjects freely challenged each other as well as forcefully argued for and against both scientifically sound and unsound ideas. Peer dialogue forces more responsibility
onto the student to make sense of the situation instead of waiting for the answer from the teacher.

**Research Methodology:**

The naturalistic methodology utilizing structured observations proved effective in gathering protocol data. After the first session all subjects seemed relaxed and uninhibited by the recording devices. Allowing the subjects to work in pairs facilitated data collection through peer dialogue, which allowed the subjects to freely discuss and question each other's ideas. Subjects over talking each other was only a minor problem for transcription. Multiple recording devices facilitated a rich collection of data, allowing omissions from one source to be filled in from another source.

**Limitations of Study**

Problems with the study included the pre- and post-instructional assessments, the tutorial itself, and student-student interactions. The pre- and post-assessments did not completely capture the subjects' naive and post-instructional models. Formal clinical interviews prior to and following completion of the tutorial would have supplemented the data.

One problem with the tutorial dealt with session five, which did not provide adequate opportunity for the subjects to apply their newly acquired understandings of potential, potential difference, etc. The application of concepts proved to be an effective way to challenge existing beliefs and reinforce new conceptions. Therefore, it was not surprising to find that the concepts associated with session five were less well developed. The tutorial did not allow subjects to return to previous screens to re-examine circuits, questions, etc. Some of the
subjects would double-click the mouse button, resulting in screens being missed. More animation would have enhanced the analogies. Several subjects complained that not enough “answers” were provided; however, this problem may have had more of an impact on subject motivation than development of understanding.

Additional problems associated with the subjects involved the length of the study. The individual tutorial sessions lasted anywhere from 45 minutes to two hours depending on the subjects and their discussions. All subjects, except Don and Heather, had visibly slowed down and lost motivation by the fifth session: It was apparent that they just wanted to finish. There were difficulties with the student-student interaction. Although friends, one pair tended to be antagonistic with each other. In another pair, one subject simply agreed with everything her partner said. The researcher was never certain what this subject did and did not understand.

Use of Concept Maps to Represent Knowledge Structures

The concept maps provided a visual representation of the subjects’ conceptual frameworks and how those frameworks changed during the instructional program. The concept maps easily represented the conceptual change processes of assimilation and accommodation. The conceptual maps do not represent the subjects’ complete knowledge structure and cannot be considered completely accurate. Rather, the concept maps represent a simplified version of the subjects’ conceptual framework based on their verbal protocols and interactions. Because the maps are simplified and static representations, they do not provide a complete picture of the dynamic process of conceptual
change. However, they do provide valuable information concerning the complexity and difficulties associated with conceptual change.

Implications:

The results of this study suggest several implications in teaching science, teacher education, and development of curriculum and instruction. The process of conceptual change was shown to be complex, intricate, and messy. The path towards greater understanding is torturous, with many backtracks and obstacles. However, science teaching that utilizes inquiry-based activities with appropriate materials does promote conceptual change and the development of more scientifically accurate models.

Inquiry-based activities need to include disequilibrating situations that take into account and challenge students’ personal theories. Conceptual change requires investigation of conceptions in a variety of contexts over a period of time. Students’ prior knowledge is an integral part of learning: To change students’ personal models, their prior knowledge needs to be challenged repeatedly and the new information tested frequently.

Proper use of analogies can promote conceptual change; however, analogies can also hinder conceptual change. The conceptual basis for the analogy needs to be clear and understood by students: for example, water flow in the water circuit analogy. The limitations of the analogy needs to be addressed frequently, reminding the student where the analogy works and where it fails. The use of multiple analogies (from different domains) enhances their effectiveness; however, appropriate “bridging” analogies (from one domain) may prove even more effective.
Teaching for conceptual change should examine and take into account the reasoning abilities and patterns of students. Inappropriate and/or ineffective reasoning will hinder the development of understanding. Of particular concern is the use of equation, formulae, and technical knowledge. Terminology, definitions, and especially equations should not be introduced until after the students has developed the conceptual (qualitative) understanding of the concept or conceptions they represent.

Curriculum development and instructional design should promote active inquiry. Textbooks and other curriculum materials need to reduce the emphasis on definitions, terminology, and equations. Curriculums that allow for investigation of phenomena in a variety of contexts, over a period of time, and at increasing complexity would provide the opportunity to challenge students' prior knowledge. Instructional methods need to promote peer interaction and active inquiry in group settings. Situations such as peer-dialogue are effective in allowing students to articulate, challenge, and refine their understanding in a less threatening situation.

The education, including preparation and professional development, of teachers needs to address the points presented above. Teachers need the opportunity to observe and/or investigate conceptual change in similar (and intimate) situations to develop a greater appreciation of the complexity and difficulty of teaching for conceptual change. For example, student teachers may achieve this experience through one-on-one tutoring. Teachers, especially student teachers, need more opportunity to design, use, and evaluate instruction aimed at changing students' conceptions. Tools such as concept mapping and analogy use need to be available for teachers to experiment and learn from.
Teacher educators need to provide direct examples of the influence of reasoning patterns on learning and to assist teachers in developing the necessary skills to recognize when students resort to mechanical/technical reasoning at the expense of developing understanding.

**Future Research**

This study suggests the following questions for further research:

1. What additional studies are necessary to better describe the process of conceptual change, especially addressing such factors as:
   - the acquisition of inappropriate conceptions and the abandonment of appropriate models for the more familiar naive models;
   - a better understanding of the mechanisms associated with changes of an entire framework compared to a section of a framework;
   - a better understanding of the refinement of a conceptual framework (similar to tuning) where information is "chunked" into categories;
   - the role of spontaneous, alternative explanations that allow students to retain personal beliefs while addressing empirical evidence that contradicts those beliefs; and
   - methods that help students recognize, use, and change their personal models?

2. How can the effects of inappropriate reasoning, especially students' reliance on mechanical/technical reasoning, be addressed during teaching, in developing curriculum, and in the teacher education? For
example, at what stage would it be beneficial to introduce equations and terminology?

3. What other types of activities, including social/peer interactions, can promote conceptual change?

4. How can the setting used in this study be adapted to the science classroom to aid in teaching and learning, as well as continued research?

5. How can concept mapping be more effectively used by the student, the teacher, and the researcher?
REFERENCES


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APPENDIX A
INFORMED CONSENT FORM
INFORMED CONSENT FORM  
*Please Read Carefully*

<table>
<thead>
<tr>
<th>Title of Study:</th>
<th>Students' Conceptual Modeling of Simple DC Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Researcher:</td>
<td>Jerian Abel</td>
</tr>
</tbody>
</table>

**HOW INVOLVED**

Developing teaching strategies, instructional computer programs, and activities that enhance learning require a detailed understanding of how students learn and process new information. The aim of this study is to document how students' ideas and beliefs change as they interact with new concepts. This study involves observing pairs of students as they work through a self-paced instructional program on simple DC circuits. The program includes the use of a computer simulation.

**PRIVACY**

This research project includes video taping and audio taping students' interactions while involved in the instructional program. In addition, the researcher's observations, notes that you might make during the program, and interviews before and after instruction will comprise the data to be collected. During transcription of the audio tapes and video tapes, all identifying names will be removed. Video tapes will only be viewed by the researcher and university faculty who are members of the researcher's doctoral committee. You are also invited to view your video tapes and to freely discuss your interpretations with the researcher. Your participation in this study will not affect your academic standing in this or any other class, at any time. Your instructor will not have access to any data that may identify you at anytime. A summary of the research findings will be available upon request.

**BENEFITS**

From this project, we hope to learn more about how students approach learning concepts associated with simple circuits. This information is extremely valuable for developing appropriate instructional programs that directly benefit students. You may directly benefit by developing an understanding of electric circuits prior to its planned classroom instruction for the physics course you are currently enrolled in.

**WITHDRAW PROCESS**

Your participation is voluntary. You are free to withdraw from this study at anytime without penalty or prejudice. Your decision whether to participate or not will not affect any present or future relationship with Radford University, this class, or the researcher. You may withdraw simply by contacting the researcher, your instructor, the researcher’s advisor Dr. Wildman (231-5598), Dr. Stout, chair of the Institutional Review Board at Virginia Tech (231-9359), or Dr. Tom Pierce, chair of the Institutional Review Board at Radford University (831-5444).
This study has been approved by the Human Subjects Committee and the Institutional Review Board at Virginia Tech, and the Institutional Review Board at Radford University. If you have any further questions, please contact Jerian Abel at either location:

<table>
<thead>
<tr>
<th>Physical Science Department</th>
<th>Division of Curriculum &amp; Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>151 Curie Hall</td>
<td>War Memorial Hall</td>
</tr>
<tr>
<td>Radford University (831-5653)</td>
<td>Virginia Tech (231-5598)</td>
</tr>
</tbody>
</table>

- This is to certify that I, ________________, hereby agree to participate as a volunteer in this investigation as an authorized part of the education and research program of Radford University under the supervision of Jerian Abel.
- The study and my role have been fully explained to me by the Jerian Abel, and I understand her explanation. I have been given the opportunity to ask whatever questions I may have had and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to deny any answers to specific items or questions in interviews or questionnaires.
- I understand that any data or answers will be treated in a confidential manner with regard to my identity.
- I understand that, in the event of injury resulting from this study, neither financial nor free medical treatment will be provided by Radford University for the injury. Further, I agree that I will not hold Radford University responsible for any liability for personal injury I may incur in the course of or as a result of the study.

- **I UNDERSTAND THAT I AM FREE TO WITHDRAW MY CONSENT AND TERMINATE MY PARTICIPATION AT ANY TIME.**

__________________________  _______________________
Signature of Participant     Date

I, the undersigned, have defined and fully explained the investigation to the above subject.

__________________________  _______________________
Signature of Investigator     Date
APPENDIX B
INSTRUMENTS
Evaluation of Conceptual Understanding
of Electric Circuits

Purpose of Test:

An instructional program for learning about electric circuits designed to monitor the development of understanding in students is currently under development. This test will be used for two purposes: First, the test will assist in the development of the computer simulation that is part of the instructional program. Second, the information will assist the researchers in recruiting volunteers for a research study that will examine how students learn as they interact with the computer simulation.

Information gathered on this form is strictly confidential. Only the researchers directly involved in this study will have access to this information. Information cannot be used in determining your academic standing in this class. All references to specific individuals on any documents will be deleted at the conclusion of the study. The study is expected to end May 1995. Student anonymity will be assured through the use of pseudonyms in all reports.

Information gathered here and during the actual research study will aid educators in developing appropriate instructional materials and strategies for the teaching of electric circuits. Your cooperation is greatly appreciated.

Part I: Biographical Information

Name:

__________________________________________________________

Academic Level (circle one):

Freshman  Sophomore  Junior  Senior  Graduate

Major: __________________________  Current GPA: _______

Reason for taking this class: ______________________________

(required for major, as an elective, general education requirement, etc.)

Did you take physics in high school? ______  If yes, what was your grade? ___

Is this your first time taking physics in college (including community college)?______

If no, describe why you are taking it now: ________________________________

1. In the picture below, draw the wire or wires necessary to light the bulb.

[Diagram of a battery and a light bulb]

Explain your answer. Be as explicit as possible (use the back of the page if needed):
Part 2:
In the remaining diagrams the symbol below will be used to represent the bulb. All bulbs are identical. All batteries are of equal strength. Do not worry whether your answer is "right" or "wrong" -- it is more important that you explain your answer.

![Bulb symbol](image)

2. The following questions refer to circuit I and circuit II.

![Circuit I and Circuit II diagrams]

a. How does the brightness of bulb A compare to bulb B? Explain your answer:

b. How does the brightness of bulb A compare to bulb C? Explain your answer:

c. How does the brightness of bulb B compare to bulb C? Explain your answer:

d. How would the brightness of bulb A change if a second, identical bulb was added to circuit I so that it was identical to circuit II? Explain your answer:
3. The following questions refer to circuit I and circuit II.

![Circuit Diagrams](image)

a. How does the brightness of bulb A compare to bulb B? Explain your answer:

b. How does the brightness of bulb A compare to bulb C? Explain your answer:

c. How does the brightness of bulb B compare to bulb C? Explain your answer:

d. How would the brightness of bulb A change if a second, identical bulb was added to circuit I so that it was identical to circuit II? Explain your answer:
4. The following questions refer to the circuit below.

![Circuit Diagram]

a. Is the current at point 1 greater than, less than, or the same as the current at point 2? Explain your answer:

b. Is the current at point 2 greater than, less than, or the same as the current at point 4? Explain your answer:

c. Is the current at point 4 greater than, less than, or the same as the current at point 3? Explain your answer:

d. Is the current at point 1 greater than, less than, or the same as the current at point 3? Explain your answer:

e. How does the potential difference across points 1 and 3 compare to the potential difference across points 2 and 4? Explain your answer:
5. The following questions refer to the circuit below:

![Circuit Diagram]

a. Compare the amount of current in the wires at points 1, 2, and 3 (that is, compare 1 to 2, 2 to 3, and 1 to 3). Explain your answer:

b. How does the potential differences across points 1 and 2 compare to the potential difference across points 2 and 3? Explain your answer:

6. The following questions refer to the circuit below.

![Circuit Diagram]

a. Compare the amount of current in the wires at points 1, 2, and 3? Explain your answer:

b. Compare the amount of current in the wires at points 4, 5, and 6? Explain your answer:

c. How does the potential differences across points 2 and 5 compare to the potential difference across points 3 and 6? Explain your answer:
7. The following questions refer the diagram below:

![Diagram of electrical circuit with bulbs A, B, C, and D and a switch]

a. Compare the brightness of each of the bulbs. Explain your answer:

b. Compare the current following through each of the bulbs. Explain your answer:

c. Compare the potential differences across each of the bulbs. Explain your answer:

d. What happens to the current through bulb A if the switch is opened? Explain your answer:

e. What happens to the current through bulb B if the switch is opened? Explain your answer:
Evaluation of Conceptual Understanding of Electric Circuits
Post-Test

1. During the tutorial, you were exposed to many ideas and concepts about electric circuits. As you progressed through the sessions, you were asked to build a model to help you explain and predict the behavior of bulbs in electric circuits. In the space below, write down your ideas that make up your model. How are those ideas related?
All bulbs are identical. All batteries are of equal strength. Do not worry whether your answer is "right" or "wrong" -- it is more important that you explain your answer.

Bulb -->  

2. The following questions refer to circuit I and circuit II.

![Circuit I and Circuit II diagrams]

a. How does the brightness of the three bulbs compare? Explain.

b. How does the current through each of the three bulbs compare? Explain.

c. How does the current through the battery in circuit I compare to the current through the battery in circuit II? Explain.

d. How do the voltages across the three bulbs compare? Explain.

f. How does the voltage across the battery in circuit I compare to the voltage across the battery in circuit II compare? Explain.
3. The following questions refer to circuit I and circuit II.

![Circuit Diagram]

a. How does the brightness of the three bulbs (A, B, & C) compare? Explain.

b. How does the current through each of the bulbs compare? Explain.

c. How does the current through the battery in circuit I compare to the current through the battery in circuit II? Explain.

d. How do the voltages across the three bulbs compare? Explain.

e. How does the voltage across the battery in circuit I compare to the voltage across the battery in circuit II compare? Explain.
4. The following questions refer to the circuit below.

\begin{center}
\begin{tikzpicture}
\node[draw,rectangle] (battery) {Battery};
\node[draw,circle,font={}] at (battery.north east) (b) {2};
\node[draw,circle,font={}] at (battery.north west) (a) {1};
\node[draw,circle,font={}] at (battery.south west) (c) {3};
\node[draw,circle,font={}] at (battery.south east) (d) {4};
\draw (a) -- (b);
\draw (c) -- (d);
\end{tikzpicture}
\end{center}

b. Compare the current at each of the points 1, 2, 3, and 4. Explain your answer:

b. How does the potential difference across battery (points 1 & 3) compare to the potential difference across the bulb (points 2 & 4)? Explain your answer:

5. The following questions refer the circuit below:

\begin{center}
\begin{tikzpicture}
\node[draw,rectangle] (battery) {Battery};
\node[draw,circle,font={}] at (battery.north east) (b) {2};
\node[draw,circle,font={}] at (battery.north west) (a) {1};
\node[draw,circle,font={}] at (battery.south west) (c) {3};
\node[draw,circle,font={}] at (battery.south east) (d) {4};
\node[draw,circle,font={}](ba) at (b) {Bulb A};
\node[draw,circle,font={}](bb) at (d) {Bulb B};
\draw (a) -- (b);
\draw (c) -- (d);
\end{tikzpicture}
\end{center}

a. Compare the amount of current in the wires at points 1, 2, and 3. Explain.

b. How does the potential differences across points 1 and 2 compare to the potential difference across points 2 and 3? Explain your answer:
6. The following questions refer to the circuit below.

![Circuit Diagram]

a. Compare the amount of current in the wires at points 1, 2, and 3? Explain.

b. Compare the amount of current in the wires at points 4, 5, and 6? Explain.

c. Which point or points best represent the amount of current flowing through the battery? Explain.

d. How does the potential differences across points 2 and 5 compare to the potential difference across points 3 and 6? Explain.

e. How does the potential difference across the battery (points 1 & 4) compare to the potential difference across points 2 and 5? Explain.
7. The following questions refer the diagram below:

![Diagram of electrical circuit with bulbs A, B, C, D and a switch]

a. Compare the brightness of each of the bulbs. Explain.

b. Compare the current following through each of the bulbs. Explain.

c. Compare the potential differences across each of the bulbs. Explain.

d. How does the potential difference across the battery compare to the potential difference across each of the three bulbs? Explain.

e. What happens to the current through bulb A if the switch is opened? Explain.

f. What happens to the current through bulb B if the switch is opened? Explain.
8. The next questions refer to this circuit. Please note that there are two switches.

![Circuit Diagram]

a. Describe the relative brightness of each of the bulbs with both switches closed. Explain why.

b. Describe the relative brightness of each of the bulbs with switch #1 opened and switch #2 closed. Explain why.

- Which bulbs changed brightness when switch #1 was opened? Why?

c. Describe the relative brightness of each bulb with switch #1 closed and switch #2 opened. Explain why.

- Which bulbs changed brightness when switch #2 was opened? Why?

c. Describe the relative brightness of each bulb with both switches opened. Explain why.

- Which bulbs changed brightness when both switches were opened? Why?
Behavior of Simple DC Electric Circuits

CIRCUIT

Open
Not Continuous
Insulators
Bulb does not light
- Bulb's black ring
- Plastics
- Glass
- Wood

Closed
Continuous Loop
Conductors
Bulb does light
- Bulb's ends
- Battery's terminals
- Wire
- Metal

"STUFF"
More stuff
Brighter Bulb
APPENDIX D
SESSION 2 TUTORIAL CONCEPT MAP
DC Electric Circuits

CURRENT

- NOT "used up"
  - round trip

- Bulb is indicator of flow

Dependent on Configuration of Bulbs

Parallel
  - More bulbs, more paths*
  - More flow

- Connected "side-by-side"

Series
  - More bulbs, greater obstacle*
  - Less flow

* Two bulbs have same brightness as one bulb

- Two bulbs are less bright than one bulb

* Inferred from water circuit analogy
Behavior of Simple

CIRCUIT

Open

Not Continuous

Insulators

- Bulb's black ring
- Plastics
- Glass
- Wood

Bulb does not light

Closed

Continuous Loop

Conductors

Bulb does light

- Bulb's ends
- Battery's terminals
- Wire
- Metal
APPENDIX E
SESSION 3 TUTORIAL CONCEPT MAP
* Inferred from water circuit analogy
Electron Flow

Ammeter
- greater needle deflects, the greater the flow

Series
- Connected in a line
- More bulbs, more resistance
- Less current
- \( I_1 = \frac{1}{2} I_2 \)
- \( I_1 = \frac{1}{3} I_3 \)

Chemical reaction

Parallel
- Two batteries, same current
- Bulb brightness does not change

Series
- Two batteries, double current
- Bulb brightness doubles
APPENDIX G
SESSION 5 TUTORIAL CONCEPT MAP
Behavior

CIRCUIT

Open

Closed

Not Continuous

Continuous Loop

Conserved

Insulators

Conductors

Multiple Pathways

Junctions

Branches can be

Current splits here

Resistance decreases

Current increases

Nodes

Independent

Dependent

Bulb does not light

Bulb does light

- Bulb's black ring
- Plastics
- Glass
- Wood

- Bulb's ends
- Battery's terminals
- Wire
- Metal

$I_{in} = I_{out}$

- Current entering a node equals the current leaving the node

- Bulbs in one part of the circuit are NOT affected by changes in another part of the circuit.

- Bulbs in one part of the circuit ARE affected by changes in another part of the circuit.
CURRENT

Dependent on TOTAL RESISTANCE

PARALLEL
- $R_T$ decreases
- $I_T = I_1 + I_2 + ...$
- As number of bulbs increase, total resistance decreases, and current increases.
- Total current equals the sum of current flowing through each branch.

SERIES
- $R_T = R_1 + R_2 + ...$
- $I_T = I_1 = I_2 = ...$
- As number of bulbs increase, total resistance increases, equaling the sum of the individual resistances, and current decreases.
- Total current remains constant throughout circuit.

Electric

Electron Flow
- $I = q/t$ coulombs per second

DC

Ammeter measures current
- greater needle defect, the greater the flow of current
- less needle defect, less current
Circuits

POTENTIAL ENERGY

- Due to separated electric charges
  - Chemical energy is transformed into electrical energy which is lost as heat and light by glowing bulb
  - Emf
    - maximum energy per coulomb
    - Units "volts"

Movement of electrons

Energy of Circuit

Potential Difference

Strength of battery

Measured by Voltmeter
  - Units "volts"

Constant Voltage Source

Elements in Parallel
  - Total voltage of circuit remains constant across parallel elements
  \[ V_T = V_1 = V_2 = \ldots \]

Elements in Series
  - Total voltage of circuit equals the sum of the voltages across each element in series
  \[ V_T = V_1 + V_2 + \ldots \]
APPENDIX H
HEATHER'S NAIVE CONCEPT MAP
APPENDIX I
DON AND HEATHER'S TRANSITIONAL CONCEPT MAP #1
APPENDIX J
DON AND HEATHER’S TRANSITIONAL CONCEPT MAP #2
APPENDIX K
DON AND HEATHER'S TRANSITIONAL CONCEPT MAP #3
TRANITIONAL MODEL #3
Don & Heather

BEHAVIOR OF SIMPLE ELECTRIC CIRCUITS

CIRCUIT

Open
Closed

Net Continuous Loop

Insulators Conductors

Roundtrip
Bulb does not light
- Bulb's black ring
- Plastics
- Glass
- Wood
Bulb does light
- Bulb's ends
- Battery's ends
- Wire
- Metal

Two Endedness of
Bulb
Battery

Source of Electrons/current

Brightness as indicator of flow
- Heating of filament because of electrons colliding.

Friction a function of resistance but not of current

CURRENT

Dependent on configuration
Independent on configuration

Parallel Series

Battery as constant current source

More bulbs, same brightness
More bulbs, less bright

Less current
More bulbs, greater obstacle less flow

Roundtrip
Junctions

More bulbs, more paths, less resistance
- Two bulbs have same brightness as one bulb
- Connected "side-by-side"

More current

Branches

More bulbs, I_1 + I_2 + ...
1/R_T = 1/R_1 + 1/R_2 + ...

Less current
More bulbs, are less bright than one bulb
- Connected "in a line"

VOLTAGE
APPENDIX L
DON AND HEATHER'S TRANSITIONAL CONCEPT MAP #4
APPENDIX N
HEATHER'S POST-INSTRUCTIONAL CONCEPT MAP
APPENDIX O
DON'S POST-INSTRUCTIONAL CONCEPT MAP
POST-INSTRUCTIONAL MODEL
Don

BEHAVIOR OF SIMPLE DC ELECTRIC CIRCUITS

CURRENT

VOLTAGE

COMPLETE CIRCUIT
Continuous Loop
Round trip path

Dependent of Configuration of Bulbs
Current Consumed
Current Conserved

Total Constant
Total Changing

Potential Potential Difference

PARALLEL
SERIES

Multiple paths
See box 1

Resistance decreases, more current
Resistance increases, less current

Current "shared" by bulbs

Box 1

\[ I = I_1 + I_2 + I_3 \]
\[ V_T = V_1 = V_2 = V_3 \]
\[ 1/R_T = 1/R_1 + 1/R_2 + 1/R_3 \]

Box 2

\[ I = I_1 = I_2 = I_3 \]
\[ R_T = R_1 + R_2 + R_3 \]

Conflicting Conceptions

Descriptive Information
Weak Conception
Misconception
Mechanical Reasoning
Uncertain Concept/Relation

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VITA

Place and Date of Birth

Education
1995 PhD, Curriculum and Instruction, Virginia Polytechnic Institute and State University, Blacksburg, VA.
1991 MS, Science Education, Radford University, Radford, VA.
1985 BS, Earth Science, Radford University, Radford, VA.

Employment
1991-95 Instructor, Physical Science Department, Radford University, Radford, VA.
1992-95 Assistant Editor, School Science and Mathematics Journal.
1992-94 Graduate Assistant, Supervisor of Student Teachers, Division of Curriculum and Instruction, Virginia Tech, Blacksburg, VA.
1991-92 Physics and Mathematics Instructor, Southwest Virginia Governor's School for Science, Mathematics, and Technology, Dublin, VA.
1989-91 Graduate Teaching Fellow, Physical Science Department, Radford University, Radford, VA.
1984-89 Research Associate, Applied Biomedical Engineering Laboratory, Pembroke, VA.

Professional Affiliations
American Association of Physics Teachers
American Association of University Women
National Science Teachers Association
School Science and Mathematics Association
The Challenger Center for Space Education

Honors
Phi Delta Kappa Young Educator Award, 1991
National Dean's List, 1984
Phi Kappa Phi Honorary Society, 1984
Sigma Gamma Epsilon Earth Science Honorary Society, 1984

Signature 9-1-95 Date