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ABSTRACT

This paper reports data collected during the first year of the Understandings of Consequence Project. This project explores how mismatched models of causality, instances when students' assumptions about how causes and effects behave significantly depart from scientific ones, may generate and/or exacerbate difficulties in achieving scientific understanding. The purpose of the project is: (1) to assess whether students hold assumptions about how cause and effect patterns unfold that can lead to alternative conceptions or misconceptions; and 2) to explore interventions that lead to scientifically accepted conceptions by increasing the sophistication of students' causal modeling. It is proposed that as students are asked to grasp increasingly complex notions of how causality works, they encounter new patterns of causal reasoning that can function as cognitive bottlenecks. Thus, at each new level there exists the risk of a mismatch between student models of causal concepts and scientific models and the potential for surmounting such mismatches through interventions that advance students' casual modeling. This study focuses on students' difficulties in learning advanced scientific concepts. Limiting the types of models students are exposed to as they learn new concepts to prevent difficulties is recommended. (Contains 38 references.) (Author/YDS)

How Conceptual Leaps in Understanding the Nature of Causality Can Limit Learning: An Example from Electrical Circuits

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This paper is based on the results of research carried out during the first year of the Understandings of Consequence Project. We are continuing to research and develop the ideas presented here. If you have feedback for us or would like to keep in touch with developments on the project, please check our website at http://pzweb.harvard.edu/Research/UnderCon.htm or send us an email at Tina_Grotzer@PZ.Harvard.Edu.

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Introduction

Students reveal a variety of alternative conceptions that are substantially different from the scientifically accepted explanations for a multitude of science concepts. A rich literature extending over the last two decades documents students' alternative conceptions or misconceptions (for reviews, see Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994). Considerable effort has been expended researching these conceptions–trying to determine sources of confusion and whether there are common patterns of reasoning that give rise to them.

While the scientifically accepted explanations may seem fairly straightforward at first glance, as soon as one scratches the surface and attempts to teach for deeper understanding, the concepts quickly become complex in a number of ways. For instance, they make reference to inferred entities that one cannot see such as protons and electrons. They involve causal patterns that extend beyond linear, unidirectional relationships, such as feedback loops and reciprocal causation. They involve causalities that are in various respects probabilistic–in that the level of correspondence between causes and effects varies. These are ways of thinking and abstractions which students typically are not familiar with.

This paper reports on data collected during the first year of the Understandings of Consequence Project. The project explores how mismatched models of causality, instances when students' assumptions about how causes and effects behave significantly depart from scientific ones, may generate and/or exacerbate difficulties in achieving scientific understanding. The purpose of the project is twofold: 1) to assess whether students hold assumptions about how cause and effect patterns unfold that can lead to alternative conceptions or misconceptions and; 2) to explore interventions that lead to scientifically accepted conceptions by increasing the sophistication of students' causal modeling. We hypothesize that as students are asked to grasp increasingly complex notions of how causality works, they encounter new patterns of causal reasoning that can function as cognitive bottlenecks. Thus at each new level, there exists the risk of a mismatch between student models of causal concepts and scientific models, and the potential for surmounting such mismatches through interventions that advance students' causal modeling.

The project attempts to address students' difficulty in learning advanced science concepts by addressing a paucity of causal models and unexamined assumptions about the nature of causality in students' understanding. This assumes that students' causal models are in some sense less than adequate for learning complex science concepts. The first part of the research project was designed to examine this assumption–to assess whether students hold assumptions about the nature of causality that can lead to alternative conceptions. The second part of the research project is to explore interventions that lead to scientifically accepted conceptions by increasing the sophistication of students' causal modeling. Researchers on the project have studied students' understanding of the following concepts: electricity, density, ecosystems, evolution, pressure and force and motion concepts.

What about the assumption that students' causal models are in some sense less than adequate for learning complex science concepts? What evidence exists to support it? Examples can be found in just about any science classroom. As students are learning about simple circuits, they typically find it hard to focus at the level of the system and try to analyze effects locally (Shipstone, 1985). They commonly employ what might be called a "cyclic sequential" causal pattern for how the current flows. They envision the circuit as initially empty and that it fills with a "substance-like material" (Slotta & Chi, 1997) which eventually reaches the bulb and causes it to light. For instance, a typical student explanation sounds like this: "The electrons travel into the wire and they go to the bulb and then it lights. The electrons keep going until they are back in the battery and can travel around again. If the wire were longer, it would take longer for the bulb to light because it takes longer for the electrons to reach the bulb." Scientists, on the other hand, might envision the system as described by a "cyclic simultaneous" causality where electrons are already throughout the wire and hooking the wire up to a battery causes flow--the excess negative charge to repel electrons which repel other electrons. The current flows all at once, more like the movement of a bicycle chain. At a broader level of explanation, scientists might describe the system in terms of differentials between and electrical potential or by a system of constraints. The students' and the scientists' models have an essentially different type of causality at the core. Students characterize wind as an active causal agent, something that is human-like in its intent and its ability to self-propel rather than seeing it as an effect of a differential between high and low pressure that results in air rushing towards lower pressure. For instance, students explain the wind in terms such as these, "the wind is air blowing that wants to go to a certain place so it pushes to get there". The student explanation encompasses a simple linear model where as the scientific explanation involves analyzing cause as embedded in an interaction or a relationship. When analyzing why an object sinks or float, students focus on attributes of the object rather than the relationship between the densities if the object and the liquid. Students typically characterize static electricity as a substance-like power that goes from one object to another–as an entity that causes effects in a simple linear pattern--rather than an imbalance of charge between two surfaces–more abstract than an entity and invoking an interactive or relational model of causality. For instance, students typically say things like, "The wool gives the balloon power that goes to the wall to make it stick."

The types of causality underlying students' models tend to be simple in form and to lead to simplified interpretations of the information in the more complex models. While simplified models may work for many aspects of explanation in our lives, they can also distort the scientific information to the point where parts of the causal story are lost or misconstrued. For instance, in the case of static electricity, students may miss the role that an induced positive charge plays and therefore may be less likely to notice related phenomenon that suggests a lightning strike is imminent. Or students may not understand why a lightning rod works.

In the following pages, we offer an in-depth look at students' understanding of electrical circuits and how notions of causality play a role in students' understanding. We share the results of an intervention study designed to impact students' thinking about the nature of causality and its effect on their understanding of electrical circuits.

An Example from Electrical Circuits

A rich literature illuminates the many misconceptions that students hold about how electrical circuits work and the nature of electrical current, in particular. Researchers have pointed to the difficulty that students have in conceiving of the circuit as a system (e.g. Dupin & Johsua, 1987; Shipstone, 1985) and in reasoning about the types of causality present in an electrical circuit (Andersson, 1986; Barbas & Psillos, 1997). In this paper, we argue that students' difficulties in reasoning about electrical circuits stem in part from elements of a persistent underlying linear causal model that students attempt to apply and from their lack of a repertoire of intermediate models of causality. We present the results of a research study designed to help students learn to think about the nature of causes and effects at levels of complexity required to understand electrical circuits and its impact on students' conceptual change.

Early research by Tiberghien and Delacotte (1976) showed that when children aged seven to thirteen were given a battery, bulb, and a length of wire and were asked to light the bulb, they typically created "unipolar" models. These "unipolar" models joined one part of the battery to one part of the bulb and described "flow" of electricity as moving from the battery to the bulb. Similar results were found with older students, seven to eighteen, by Osborne and Gilbert (1980) and by Andersson and Karrqvist (1979), and with university students by Fredette and Lochhead (1980). These unipolar models fit with a simple linear model of cause and effect in which one thing typically makes another thing happen in a domino-like pattern of effects. There is temporal priority between cause and effect--causes always neatly precede effects--and there is usually one cause and one effect (Grotzer, 1993).

Andersson (1986) has argued that this simple linear arrangement fits with our most primitive notions of causality which Lakoff and Johnson (1980) first called the "experiential gestalt of causation (ECG)". At a very early age, children learn to expect this pattern. Andersson argues that as children act upon their environments, they learn that actions by an agent (themselves) can impact objects (such as toys, blankets, bottles, and parents.) The relationship is one-to-one. Intensified efforts by the agent lead to an intensified impact on the object. Children discover that the nearer the object, the greater the effect. Andersson argues that this underlying pattern of reasoning or "ECG" can be seen in students' thinking in a variety of science concepts.

Further, Bullock, Gelman and Baillargeon (1982) suggest that we may be "hard-wired" to expect certain causal contingencies to hold. These include *determinism*, the expectation that physical events are caused; *mechanism*, the assumption of the transfer of causal impetus, either directly or through a chain of events; and *priority*, the assumption that causes precede or coincide with their effects and that the causal relation is always unidirectional. While Bullock and colleagues (1982) allow for causes and effects that coincide, we expect that nonscientists may not. Further, Leslie and colleagues (1982; 1984; Leslie & Keeble, 1987) and Spelke and colleagues (Rubenstein, Van de Walle, & Spelke as cited in Spelke, Phillips, & Woodward, 1996) have shown that infants apply a principle of contact to physical causality and that action at a distance violates this assumption.

We argue that causal contingencies such as those outlined by Bullock and others can lead us to impose broad patterns of causal expectations that are elicited when learning science concepts and that these patterns may need to be addressed in helping students evolve more sophisticated concepts. For instance, assuming that a cause always temporally precedes an effect may lead to imposing a *linear sequential causal* pattern of explanation. When teaching students to conceptualize a circuit, educators have tried using the analogy of a bicycle chain to help students visualize the causal pattern in play. The bicycle chain analogy requires students to switch to a *cyclic simultaneous causal pattern* in which causes and effects co-occur, as in the case of electrons being repelled and repelling when electrical current is flowing in a steady state. If students impose a linear sequential causal pattern in learning about simple circuits, they may miss the deep structure of the bicycle analogy or distort parts of it to fit a linear model.

Others have made similar arguments. Barbas and Psillos (1997) have argued that students' patterns of causal reasoning influence how students are able to reason about simple circuits. They note that several previous researchers have modeled students' reasoning in terms of simple and linear causality (Andersson, 1986; Cheng & Holyoak, 1985; Rozier & Viennot, 1991) but that few, if any, concerned students' ability to reason cyclically. They argued that understanding the simple circuit engages students in understanding iterative causal chains in the form of a general circular causality where A —>B—>A either sequentially or simultaneously.

The extant research supports that students bring causal intuitions to their learning. For instance, di Sessa (1993) introduced the concept of phenomenological primitives (or p-prims), small self explanatory knowledge structures that people rely on in constructing explanations or components of explanations. He identifies many different p-prims that people use in their explanations. For instance, the p-prim of "dying away," in which people recognize that earthly motion essentially always "dies away." This phenomenon can be explained in more complex terms such as friction and dissipation, however, people typically feel satisfied that "dying away" is enough of an explanation. However, unlike the causal expectations we have outlined above, p-prims are not part of a larger unifying theory and di Sessa is skeptical about attempts to unify them. Other research by Brown (1995) refers to core causal intuitions (for example, initiating; initiated; and reactive) regarding how people attribute agency and assess responses to agency that can make it difficult to learn certain science concepts. Brown's set is somewhat more theory-like than di Sessa's and might operate as part of the causal patterns outlined above or as a reinforcing aspect of one. We expect that sets of assumptions such as those outlined by diSessa, Brown, Bullock, Spelke, and others can work in combination to create larger-scale causal patterns that constitute students' typical default patterns. These patterns make sense to students and may persist even when students have learned more complex models.

Not all researchers agree that the underlying linear causal model to describe a simple circuit is robust enough to persist once students have had experience with batteries and bulbs. According to Dupin and Johsua (1987), the belief that one wire can give electricity to the bulb and light it is not a resistant belief; it often disappears in the course of only one lesson. While indeed, students discover that this arrangement will not light the bulb, we argue that the underlying causal structure of this model is resistant and that even when students begin to depart from a linear model, they retain aspects of it in their interpretations of the circuit.

An examination of the progressive understandings identified by Shipstone (1984, 1985) can be used to illustrate the persistent aspects of a linear causal model. Shipstone (1984, 1985) found that students' models for understanding a circuit progressed through a series of five models. Originally, students used a linear or "sink" (Fredette & Lochhead, 1980) model in which a single wire running from the battery to the bulb "gave" electricity to the bulb in a consumer source relationship. Students' understanding then progressed through a "clashing currents model" (Osborne, 1981) in which electricity travels up from both terminals of the battery and up both wires and meets or clashes to fuel the bulb. Students then typically progressed to a "lessening currents model" in which they envision current as flowing in one direction around the circuit and as being used up so that there is less available to other components further along in the circuit. Eventually, students moved to a shared model in which current is shared between the components in the circuit but is still used up. Finally, students moved to a scientific model in which the current is conserved throughout the circuit.

The sink (Fredette & Lochhead, 1980) or basic consumer source (Shipstone, 1985) model represents a simple linear cause and effect relationship. It fits with the linear, "agent directly acting on an object" relationship identified by Andersson, outlined above. The clashing currents model concatenates two causes to lead to the effect, yet retains the linear structure as well as the domino-like sequential pattern and the temporal precedence of causes to effects. A lessening currents model introduces the iterative nature or reciprocity of a cyclic pattern, however it retains the sequential, domino-like aspects of the linear model. The shared current model is the first model that clearly departs from a domino-like pattern of events and begins to move away from temporal precedence of causes to effects.

Research shows that when students hold cyclic models, they tend to hold "cyclic sequential models" in which the current travels from point to point and affects each component in turn as it is encountered within the circuit (Closset, 1983; Shipstone, 1984). In a cyclic sequential model, students typically envision the circuit as initially empty and filling with a substance-like material which eventually reaches the bulb and causes it to light. The sequential causal model is particularly resistant to change. It has been found even in students who have taken university courses and passed university level exams in physics (Picciarelli, Gennaro, Stella & Conte, 1991). In order to conceptualize current flowing in a steady state, students need to visualize a "cyclic simultaneous model of causality" that has no clear temporal precedence. In this model, the circuit is viewed as already having electrons all along the wire that simultaneously repel those in front of it and are repelled by those behind it. The whole thing moves at once as in a bicycle chain and it is the flow of electrons (as opposed to electrons "reaching" the bulb) that causes it to light. It is not easily constructed from linear causal models as a cyclic sequential model is. It helps students to focus on the circuit as a system and serves as a connection to a less zoomed-in level of analysis and to electrical potential models in which differences in electrical charge across the entire system enable electrical vibrations to propagate through the system.

A Progression of Electrical Models Based on Conceptual Leaps in Underlying Causal Pattern

The argument that linear causal models are resistant and that students need to learn more complex forms of causality in order to master the scientific understandings assumes a vision of what those more complex forms of causality are and how they relate to the scientific understandings. What are the scientific understandings that students move towards with deeper understanding and what intermediate conceptual models might help them to get there? Figures 1-5 introduce a proposed sequence of conceptual models that progress towards a more scientific understanding of how a simple circuit works.

We devised this progression drawing from the extant research and our research into students' ideas about why the simple circuit works. These models differ slightly from those of Shipstone (1984; 1985) in that they are grouped by the causal assumptions that one needs to make to in order to understand them and the conceptual leaps needed in understanding causality in order to progress from one set to the next. Because we hypothesized that students' limited understanding about the nature of causality impedes their ability to learn more complex science concepts, we organized the models to reflect the kinds of causal rules that students needed to learn to grasp each type of model and to progress in their understanding of causation in electrical circuits. The models also depart from those in earlier research in that we offered students intermediate causal models that aimed to explain the "why" behind current flow, rather than focus on "how" as Shipstone's later models do and as a constraint-based model that focuses on the constraint between voltage, current, and resistance would. The models we are proposing as intermediate conceptual models are visualizable, a criterion that Gobert and Clement (1999) suggest is important for students' ability to learn them. They fit with what Perkins and Unger (1994) have called "stripped down visual analogs." They are simplified visual diagrams designed to clearly communicate the basic understandings without additional clutter to create excess cognitive load. The first few models overlap directly with those of Shipstone (1984; 1985) in that they begin where the students begin (with various forms of linear models). In the context of the study that follows, we did not introduce these to the students, rather the students brought these conceptions and therefore we began with them.

Figures 1-5: A Sequence of Conceptual Models that Progress Towards a More Scientific Understanding of How a Simple Circuit Works Based on New Sets of Causal Assumptions

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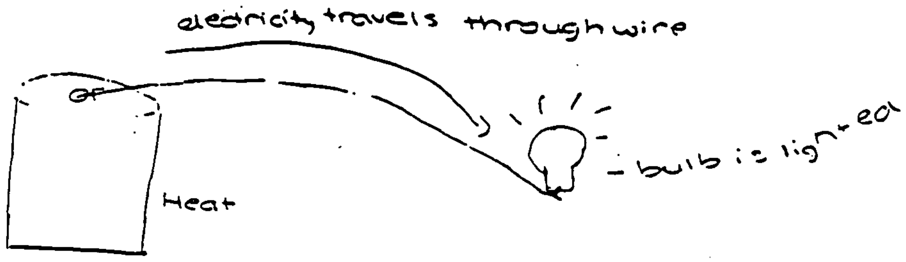
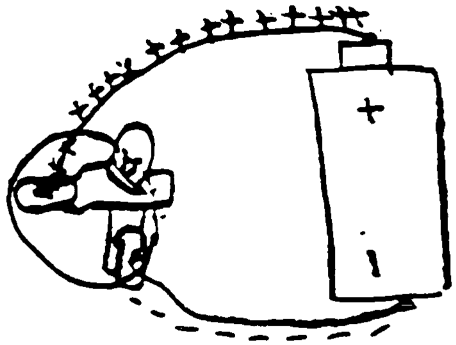
Fig. 1: Simple Linear Causal Models:



Simple Linear Model- A single wire running from the battery to the bulb "gives" electricity to the bulb in a consumer source relationship. Note that current is not conserved, there is nothing to account for the "flow."

Fig. 2: Double Linear Causal Models:

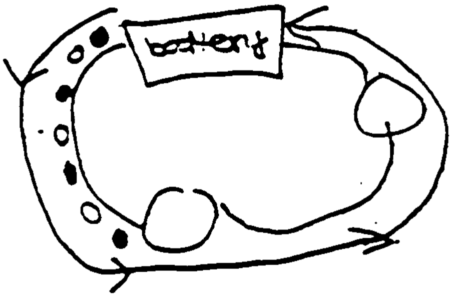


Double Linear Models: Clashing Currents or Attraction Models- Electricity travels up from both terminals of the battery and up both wires and clashes or attracts to fuel the bulb. Note that current is not conserved, the attraction of protons and electrons accounts for the flow, and it gives an accounting of why you need two wires or to have a "circuit."

Causal Characteristics of Simple Linear and Double Linear Models:

1. Something goes from the battery to the bulb in a linear, unidirectional pattern.
2. That agent or substance does something to or within the bulb to make it light (feeds it, attracts, clashes, cancels out.)

Fig. 3: Cyclic Sequential Causal Models



Current flows in one direction around the circuit and is being used up so less is available to other components further along in the circuit. Students typically expect a delay that increases with the length of the wire you use or that there should be a resulting delay in when bulbs further along the circuit light up. Other students believe that there will be no delay and that electrons or electricity somehow can anticipate the length of the wire and speed up as necessary. Some students hold onto aspects of a consumer-source relationship even though they know that the flow needs to be cyclic. They may say that "some current is used up." Note that current is not entirely conserved though some of it is seen as recycled, the attraction of electrons to the protons (which don't move) accounts for flow, it and it gives an accounting of why you need two wires or to have a "circuit." Electricity is viewed as substance-like and the circuit is viewed as initially "empty."

<u>Causal Characteristics of Cyclic Sequential Models:</u>

1 A substance-like matter leaves the battery and causes the bulb to light in a linear sequential pattern. It goes around and into the battery and is recycled in a cyclic pattern.
2. There is a beginning and an ending of sorts at the battery. Once the electrons get back to the battery, they begin again. Viewed ahistorically, once the circuit is flowing, it resembles the cyclic simultaneous model.

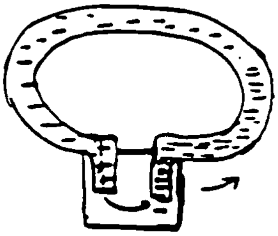
Fig. 4: Cyclic Simultaneous Causal Models

The wire is made up of atoms so it has electrons and protons all along it. Once you hook the battery and bulb up completing the circuit, electrons are repelled or pushed out of the battery on the negative side (and to some extent pulled into the battery on the positive side.) This makes the whole circle of electrons turn. Each electron repels the electrons ahead of it on the wire and is repelled by those behind it. The whole circle moves as one like a bicycle chain. Instead of one thing happening at a time, it happens all at once--it is nearly simultaneous. The chemicals in the battery do the work of polarizing the protons and electrons to the plus and minus sides of the battery. Note that current is conserved, the repelling of electrons from electrons accounts for flow, and the wires which are made up of electrons and protons are already filled at the start and it is the movement or flow that causes the bulb to light.

Causal Characteristics of Cyclic Simultaneous Models:

1. There is no real beginning or ending, at least not once it gets started going.
2. Something can be a cause and an effect.
3. Cause does not precede effect temporally.
4. Cause is distributed around the circle.

Fig. 5: Relational or Interactive Causal Models



The concept of "electrical potential" or "potential difference" requires that students understand the circuit relationally–in terms of a differential. This is a relational or interactive model. The battery performs work by supplying "push" or "tension." The higher the voltage of the battery, the more work the chemicals in battery are able to perform pushing electrons away from the protons that they are attracted to and towards electrons that they are repelled from. Therefore, the more voltage, the more electrons the battery can concentrate on the negative terminal. In this model, the cause of flow is visualized in terms of the relationship between areas of greater and lesser concentration or density. Electrons will move from areas of higher concentration to areas of lesser concentration, therefore, they move onto the wire where there is less concentration and continue moving on it as the battery continues to concentrate more electrons on the negative terminal.

Causal Characteristics of Relational Models:

1. The outcome is caused by the differential relationship between elements of the system.
2. Neither "status" (more or less concentration of charge) is the cause by itself.

Each of these intermediate conceptual models involves students in new challenges in terms of how they think about cause and effect. And yet it is highly unlikely that students are aware of the implicit causal expectations that they hold or typically have instructional experiences that will help them to learn to think about the types of causality that each model entails.

Research by Barbas and Psillos (1997) promises that student can learn more sophisticated causal models. Working with pre-service teachers, they found that through a teaching sequence of questioning, explanation, and discussion, they were able to get movement from less toward more causally complex reasoning patterns. For example, the following excerpt of an explanation by one of their subjects reveals a cyclic simultaneous type of causality:

> "Then the electrons in the wire...They push one another. Yes, first those closest to the negative terminal, are repelled by the negative [charges] of the terminal, then those repel those next to them, etc., so that all move from the negative terminal of the battery towards the positive terminal (Student 6)." (pg. 451.)

This paper reports on the first of a series of research studies designed to test the result of making students aware of their current notions of cause and effect and to engage them in thinking about the nature of more complex forms of causality in analyzing instances of causation involving electrical circuits. We focused directly on the conceptual leaps that students must make in order to understand the causalities embedded in the models outlined above. Based upon the previous research, we hypothesized that we would find many linear causal models in students' initial conceptions and that the teaching challenge would be to help move students to cyclic models, particularly cyclic simultaneous models, if possible. (With older students in research that will be reported elsewhere, we attempted to move students through the cyclic simultaneous models to models of electrical potential.)

Deeply understanding cyclic causality requires making a leap from iterative causal chains to a causality in which temporal precedence between cause and effect is either nonexistent or obscured once things get started and the distinction between cause and effect is easily blurred. Cyclic sequential models retain the temporal sequence of linear models as they are getting started in that the effects unfold over time and each effect in turn causes the next effect. In contrast with linear causality, the effects do continue on to precipitate another round of the causes. At this point, temporal precedence becomes obscured. Cyclic sequential models, then, if not viewed ahistorically, retain some of their linear aspects. The conceptual leap to viewing them ahistorically then is not inconsequential. Perhaps they offer a bridge to more complex cyclic models where temporal precedence is obscured. For instance, in cyclic simultaneous causality (while recognizing that there is a imperceptible transient delay until the circuit is at steady state), the cycle is connected at all points and all parts cause and impact all other parts all at once. In the teaching of electricity, researchers have likened this to the movement of a bicycle chain (which also exemplifies the analogous transient delay of the electrical circuit) (Shipstone, 1985).

The cyclic simultaneous model necessitates that students begin to perceive the circuit as a system and to consider its behavior as a whole rather than focusing on parts of it (as the cyclic sequential model allows). Previous research (e.g. Cohen, Eylon, & Ganiel, 1983) showing that students tend to engage in local analysis of changes in the circuit suggests that this conceptual switch is particularly challenging for students. It also requires that students use a process notion of electrical flow rather than a substance notion (as they can with a cyclic sequential model). Slotta and Chi (1999) and Slotta (1997) have found that a substance notion of the electrical current as opposed to a process notion creates a major stumbling block for students learning to think about electrical circuits. Heller and Finley (1992) found that of the many misconceptions that teachers hold about the nature of the circuit, some were "hard-core" and are seldom modified or compromised as teachers attempt to reason across different problems. Amongst these was the belief that "the circuit is initially empty of the "stuff" that flows through the conductors." (p. 268.) This belief fits firmly with a cyclic sequential model but not a cyclic simultaneous one.

Beyond this, moving from a cyclic simultaneous model to an electrical potential model involves another set of conceptual leaps in how one thinks about causality. Conceptualizing the circuit in terms of potential difference involves seeing it as a system and reasoning relationally in terms of quantities of protons and electrons. The cause of flow is seen as a differential. It embeds many of the concepts of the cyclic simultaneous model, for instance, that there is no real beginning and ending (unless the differential is lost.) In terms of causality, students need to shift their focus from the action of an entity or entities (movement of electrons) to the result of a relationship of imbalance. The causal agent is more difficult to detect because it is more abstract and because students tend to seek out entities as causal agents.

Whether it makes sense to view electrical circuits as a causal system at all has been questioned. Chi and Slotta (1993) argue that these are acausal processes and are taught by teaching laws or constraint-based systems. We argue each type of model has its place. It depends in part upon what level of explanation one is seeking to clarify. Others have argued that students benefit from visualizable, conceptual models upon which they can base their reasoning (Gobert & Clement,1999). Johnson-Laird (1983) suggests that more powerful reasoning results from the use of models than from inferential rules. A wealth of research shows that when information is presented in a manner that is organized by causal and temporal order, children are much more successful at recalling it and mapping it to analogical problems (e.g. Slackman & Nelson, 1984; Slackman, Hudson, & Fivush, 1986). The research of Shipstone and others (1985) shows that students construct explanatory models on their own of how and why electrons flow. It makes sense to help students fill in the blanks with models that can help them reason about related concepts such as parallel and series circuits, alternating versus direct current, and so forth.

One manner of dealing with the difficulties that various causal models pose for learners is to limit the types of models students must deal with while learning new concepts. White and Frederiksen (1990; 1995; White, 1993) exposed students to models that were *causally consistent*, for instance, in which electrical force was the causal agent in both qualitative and quantitative models when learning the behavior of electrical circuits. They argued that, to the extent that there was *causal generality* in the concepts and laws embedded in the models, students should be able to apply their understanding to other domains (White & Frederiksen, 1990). The present research asks a slightly different question. It asks how we can engage students in thinking about the nature of causality itself in an effort to build their ability to handle a variety of complex causal models in order to help them achieve the scientific understandings.

We conducted an intervention study to offer insights on the following questions: *1. What causal patterns do students expect in their initial explorations of electrical circuits?* We expected that these patterns would fit with the previous literature and that, as in the extant literature, students' expectations would fit with what would be predicted by component concepts such as temporal precedence of causes to effects, determinism, and so forth. *2. What is the effect of engaging students in activities to introduce intermediate conceptual models in the context of learning about electrical circuits?* We expected that students needed opportunities to engage in activities that allowed them to construct and consider a variety of intermediate causal models to explain the causality behind the simple circuit. We did not expect, however, that the activities would be enough to help students make the conceptual leaps required by the models if indeed, understanding the nature of different types of causal patterns functioned as a bottleneck in learning the models. *3. What is the effect of explicitly discussing the nature of the types of causality embedded in the intermediate conceptual models?* We expected that students' beliefs about the nature of causality are so ingrained and at the same time, so inaccessible to them, that targeted interventions to address their causal assumptions would be needed in addition to the opportunity to construct and incorporate new ways of thinking about causality in order to understand the intermediate causal models.

Method

Overview:

Students and teachers in three 4th grade classes participated in the following research design. All three classes were given an inventory to assess their initial knowledge of static and circuit electricity. In addition, nine students from each class were interviewed in depth about the causal models that they held for analyzing electricity problems. Each class then participated in a three week (with two classes per week) mini-unit on static electricity which was not part of the teachers' regular curriculum. The static unit was followed by participation in the NSRC Electrical Circuits Unit, which is a regular part of the teachers' curriculum, for approximately ten weeks (with two classes per week). For one of the classes--the causal models (CM) group--activities were infused to help students focus on the underlying causal patterns and explicit discussions of the causal patterns were included throughout the unit. For a second class--the activities (AO) group–the activities but not the explicit discussions were included. The third class functioned as a control group and participated in the static and electricity unit without the activities or causal discussion components. At the conclusion of the units, all of the students participated in a post-inventory and the students who were pre-interviewed were post-interviewed. Students who participated in the causal models group were interviewed on what aspects of the causal models were more or less difficult for them. A similar research design was carried out with 8th and 11th grade students and although those results are not reported here, some of the examples are taken from those students where noted.

Subjects

The students were fourth graders from two elementary schools in the Boston-area. One of the schools was chosen in part for its ethnic diversity and mixed SES population. The other school is less diverse so it was decided that these students would participate in the control group. A total of seventy-two students participated in the formal study with 27 of those students participating in in-depth interviewing. There were approximately equivalent numbers of boys and girls in the groups. In addition, a fourth class participated in pilot-testing the materials but were not part of the formal study.

Procedure

Pretest:

We developed and group-administered a pre- and post- inventory consisting of 14 multiple choice and two essay questions. The inventory was pilot-tested on a group of fourth grade students who were not participating in the study and was revised based upon their performance, their comments, and the comments of their teacher. The resulting inventory included questions that would reveal correct or incorrect scientific knowledge that would likely derive from the type of model that students held for an electrical circuit. For instance, "Which of the two students do you agree with most? Circle a or b." with the following answer choices: " a. The first student said 'when the bulb is lit, there is electrical current flowing around the circuit. There is the same amount of current flowing from the bulb back to the battery as there is from the battery to the bulb.' or b. The second student said, 'There is electrical current flowing only from the battery to the bulb. The current is used up by the bulb.'" Other questions asked students to analyze series and parallel circuits and tell whether both bulbs would light, whether there would be differences between them and so forth.

Nine students were interviewed from each class using a clinical interview with three levels of scaffolding. Teachers were asked to choose the students to be interviewed and to balance these groups so that there were three low-, middle-, and high- achievers in each group. The achievement ratings were based on teachers' subjective assessments after having had the students in their classes and becoming familiar with students' histories for the first four months of the school year. The interview began in an open-ended way to see what causal expectations students brought on their own. For instance, students were given a battery, a bulb, and a set of wires and were asked what they would do to light the bulb and why they thought that arrangement would work. Students were told that something had been changed inside the battery so that it would no longer work so that the session would test students' expectations about what they thought should work rather than their ability to experiment and find a model that worked. The interview progressed to more targeted questions to see whether students would choose the scientific model if it was offered as a choice. In addition to the task focused on simple electrical circuits and how and why they work, two other tasks assessed students' understanding of static electricity with a balloon and wool and in the case of lightning. Those tasks are not analyzed as part of this paper.

Intervention:

The classes all used an inquiry-based mediated-constructivist approach. Two researchers became part of the scientific community in the classes for the time period of the units. Since the teachers had revealed the same misconceptions about why the bulb lights as the students, many of the lessons, particularly those focused on causal explanations were taught by the researchers. The NSRC unit includes the opportunity to investigate what happens with batteries and bulbs. However, it does not involve modeling of students' ideas–the drawing and explaining of what students think is going on at a causal level in relation to various phenomena. In all of the three classes, opportunities were infused for students to model and discuss their ideas. Students were asked to draw what they thought was going on causally at different points in their experimentation and to revise their ideas as they discovered new information that contradicted their earlier models. Students kept journals and tested and discussed their theories in light of the evidence that they found.

In the course of the NSRC unit, students are not offered a causal mechanism for why the bulb lights beyond the explanation that it is a complete circuit. Rather, students (and teachers) are left to fill in the blanks as to why a complete circuit works. It was decided that in order for students to understand the behavior of electrons in the circuit, they needed to know about how electrons and protons behave when they are not in a circuit. Therefore, a mini-unit on static electricity was added for all three classes before the unit on electrical circuits to introduce the particle model of electrons and protons and attracting and repelling. It was based partly upon materials developed by AIMS for the intermediate grades and partly on activities developed by the researchers.

During the NSRC electrical circuits unit, for the intervention groups, activities were added to the unit to focus on the underlying causal models. Through role-playing and a variety of sets of models (for instance, using marbles and tubing), students were invited to think through the implications of various models including the scientific one. Students in both the CM and AO groups were shown the various models and engaged in the roleplaying activities for comparing a cyclic sequential and cyclic simultaneous model. Students in the CM group were taught that the circuit, after a transient delay, operates according to cyclic, simultaneous causality with flow sustained by the repelling of electrons (each electron playing the role of both cause and effect) along the circuit and were invited to contrast this with cyclic, sequential causality and linear causality. They contrasted and discussed the different types of causality. For instance, here is an excerpt of class discussion:

> T: Let's compare how cause and effect works in these two different kinds of cyclic models. In the cyclic sequential one, what makes the electrons move?
> S1: They want to get out of the battery because of all the electrons so they go onto the wire.
> T: Okay, and then what happens?
> S2: They go along the wire till they get to the bulb and that makes the bulb light up.
> T: Why do the electrons move in the cyclic simultaneous model?
> S1: The electrons push the one in front but at the same time they are pushed by the one before them.
> T: Right, in a sense, each electron repelling is the cause of the next one but it is the effect of the one behind it. It's both a cause and an effect at the same time. What you get is the whole thing turning like the chain on a bicycle. What cause the bulb to light?
> S3: When the electrons start to flow.

During the course of the unit, we collected students' journal entries and answers to specific questions designed to assess how their understanding was progressing.

Scoring:

Whole Class Electricity Inventory:

The multiple choice portions of the inventory were scored in the following way. Students were assigned a general score for all inventory questions. This included questions that focused on particular model-based misconceptions as well as those that tested knowledge that was not specifically linked to particular misconceptions.

One essay question asked how a switch works to turn things on and off. We were specifically interested in the kind of language that students used to describe what the switch does. Some language suggests that the switch is a gate that is responsible for keeping something out. For instance, "when the switch is open it allows electricity to pass through" or "something blocks the electricity to keep it from getting through." Many of these explanations tended to be very substance-like and fit with descriptions found by Slotta and Chi (1999). For instance, one student said "the wire is like a rubber hose and the electricity runs through it, when you turn the switch off, you shut it off." Other language suggests that the switch stops the flow of something. For example, "it reconnects or disconnects a circuit. When it disconnects, it stops the flow of electrons." Students' explanations were scored for whether they represented substance or process explanations. Substance explanations (which typically accompany a cyclic sequential model) refer to the switch as a gate that does not allow a substance-like material to reach the bulb, thus keeping the "inside" of the wire "empty." Process explanations (which more commonly accompany a cyclic simultaneous model) refer to the switch as something that stops the simultaneous repelling of electrons along the entire circuit.

The second essay asked the students to consider whether, if you increased the length of the wires in a pictured circuit, it would take longer or approximately the same amount of time for the bulb to light and asks the students to explain why. Specifically, we were interested in whether students revealed a sequential notion of electron "flow" or a simultaneous one. Sequential models were typified by the idea that the electricity or electrons have to reach the bulb while simultaneous models were typified by the idea that the electrons are already along the wire and that the flow of electrons was responsible for the lighting of the bulb rather than the electrons reaching the bulb. The following kinds of statements were scored as indicating a sequential model:

> "It would take longer because the electrons need to flow through the wires to get to the bulb."
> "It would take longer because even though electricity travels fast, it still takes longer to get there."
> "It won't take longer because the electricity will somehow make up the difference by traveling faster."

The following kinds of statements typified simultaneous models:

> "It wouldn't take longer because the wire is made up of atoms and they get pushed as others get pushed out of the negative side of the battery and get pulled toward the protons on the positive side."
> "It wouldn't take longer because there are atoms along the wire and as soon as you hook it up, it begins to flow. The flow makes it light up."

Students protocols were also scored for whether they revealed mixed models, other models, or were otherwise unclear or unscoreable. Other models referred to ones that were neither simultaneous or sequential. For instance, some students revealed what might be called "assistance models" ("I think that the A wire is helping the B wire to light the bulb.") or "attraction models" ("The negative and positive meet in the bulb to make it light.")

It was also considered whether or not the student thought it would take longer or the same amount of time for the bulb to light. This information alone is not meaningful and depends upon the student's explanation. Students who held sequential models typically thought that the more the wire length was increased, the longer it would take for the bulb to light up while students who held simultaneous models typically did not believe that it would take longer to light up. However, the possibility existed that some students would reason that there might be a transient delay even though the process is nearly a simultaneous one. This is a rather sophisticated line of reasoning, but one that better fits the scientific explanation than a purely simultaneous model.

The scoring scheme for the essay questions was developed and refined. Then two scorers each scored 100% of the data. Initial agreement was assessed using a Pearson Product Moment Correlation (r = .87) on Essay One and (r = .91) on Essay Two. Differences were discussed until 100% agreement was reached.

Interview Data:

The interview data was globally scored to determine what type of model it represented. Scores were then attached to each model type, reflecting the level of complexity that it involved.

No Causal Model = 0 points:
Responses that did not contain a clear causal model were scored as zero. This included responses that referred to background conditions or supplied peripheral information (i.e. "You need to have a battery." "The wire has to be metal."); those where the subject did not appear to have a predominant idea (or even multiple competing ideas to characterize how the circuit works). (i.e. "I don't know." "I've never thought about this before." "I don't have any ideas."); and instances where students gave a configuration only but were unable to offer an explanation of why it actually worked.

Simple Linear Causal Models = 1 point:
Responses revealing simple linear models were scored as one point. These included: "token or entity explanations" which do not go beyond the idea that electricity causes it to light up. Electricity (or something like electricity) stands in as a causative agent in a token way. (i.e. "Electricity makes it light." "Power makes it light.") Other simple linear responses included linear consumer source models characterized by a single wire running from the battery to the bulb. The battery is viewed as giving electricity to the bulb in a consumer source type of relationship. There is a notion that stuff from the battery travels to or is delivered to the bulb. (i.e. "The battery gives energy to the bulb." "The stuff from the battery flows up the wire and gives electricity to the bulb.") It also included linear models with electricity passing through" which were characterized by electricity flowing up and through the bulb, but the model appears to stop there. There is no mention of the recycling of electrons.

Double Linear Causal Models = 1.5 points:
Responses revealing double linear models were scored as 1.5 points. These models included: linear models with passive assistance or additive aspects that are characterized by a linear relationship where a second wire *passively* contributes to the lighting (acts as a ground, etc.) (i.e. "The other wire is a ground." "It's for safety." "The other wire has to be there or it won't work.") It included linear models with active assistance or additive aspects characterized by a double linear relationship where the second wire in an *active* way contributes to the lighting (makes it stronger, fuels it, etc.) But not in the very specific causal modes that follow, clashing currents or attraction models, do. (i.e. "You need two wires to get enough power to make it light." "The electricity goes up both wires to make it light.") Finally, it included "clashing currents" or attraction models characterized by electricity traveling up from both terminals and attracting or clashing to fuel the bulb. (i.e. "The electrons travel up one side and the protons travel up the other and they clash together to make it light.""The electrons come from one side of the battery and the protons from the other and they attract and meet in the bulb.")

Cyclic Sequential Causal Models = 2 points:
Cyclic sequential models were scored as 2 points. These are characterized by the electricity/electrons traveling around the circuit in a sequential manner. They start out at the battery and travel to the bulb. Typically the students expect a delay in when the bulb lights if they hold a sequential model. (The electricity needs time to get to where the bulb is.) Typically students believe that the electricity is used up by the bulb or at least some portion of it is. This model often has consumer-source aspects but they are not linear. (i.e. "The electricity goes along the wire in a circle and when it gets to the bulb, the bulb

lights up. Then it keeps going back into the battery and goes around again.")

Cyclic Simultaneous Causal Models = 2.5 points:
Cyclic simultaneous models were scored as 2.5 points. These are characterized by electricity/electrons already existing in the circuit and simultaneously repelling each other as more electrons are repelled onto the wire by the battery. (i.e. "The electrons are pushed by the electrons behind it and that makes them all flow and makes the bulb light." "The electrons are trading partners and when they do it makes all of them move like a bicycle chain and the bulb lights up." "All of the electrons are moving at once." "It doesn't go one at a time. It goes all at once.")

Relational Causal Models = 3 points:
Finally, relational causal models (of which there were none in the fourth grade data) were scored as 3 points. These are characterized by electrons flowing away from areas of greater concentration towards areas of lesser concentration. The cause of the "flow" is a differential relationship that results in electrical potential.

In some cases students merged more than one model. These were instances where the student created a model that had aspects of two of the types of models or wavered between two models. In these cases, the scores of the models were averaged. There were numerous cases where students began their explanation with more simple models and as they explained, then progressed to more complex models. In these cases, the model that students ultimately settled upon was scored. The interview was scaffolded so that students answered the question first in an open-ended manner and then had the opportunity to choose from a set of answers and offer an explanation for their choice. Typically, students chose the answer that fit with the model that they had given. When students changed their answer, these two models were averaged to yield an overall score. There were a few cases where students offered a model other than those presented above. However, students who did this also gave one of the models above and they were given the score corresponding to that model.

Students' interviews were transcribed and then scored by two independent raters. A Pearson Product Moment Correlation was conducted and initial agreement was assessed at ($\underline{r}$ = .92). The differences were discussed and resolved until there was 100% agreement.

Results

How were Students' Initial Causal Models Characterized?:

Students' initial causal models on the pre-interviews fit with those that were expected based upon the previous research. Figure 6 is a chart summarizing the number of students using each model type on the pre-interview across all of the groups (n = 27). Only two students of those interviewed (n = 27) used cyclic causal models to explain the nature of flow in the current. These models were cyclic sequential models that viewed the circuit as initially empty and slowly filling step by step until it reached the bulb which would then light and continuing on around until the current again reached the battery. Of the remaining 25 students interviewed, four did not offer what would be called causal models at all in that they did not include a causal mechanism or clear causal pattern. Rather, they referred to background conditions. For instance, "You have to have a battery" or "The kind of wire matters." Ten students used simple linear causal models, eleven students used forms of double linear models (where the current flowed up both sides of the wire and clashed or was attracted due to "positive flow" and "negative flow") and two students used cyclic sequential models. No students used models that revealed an understanding of electrical potential or imbalance as the cause of flow.

The teachers involved with the project all expressed cyclic notions of causality to describe the circuit. However, some of their models appeared to be sequential. In an activity in which the students were asked to line batteries up to light a household bulb, one teacher asked her students to observe how much longer it took for the bulb to light as they added batteries. While there certainly is a transient delay, it's not anything that students will perceive. Another teacher described a series circuit as the electricity travels from one bulb, then it goes to another, then to another. Her choice of language could reinforce a cyclic sequential causal model and the idea that electrons reaching the bulb rather than flowing through the bulb are what causes it to light.

This fits with previous research which suggests that teachers often hold the same misconceptions as do their students (e.g. Lawrenz, 1986). Heller and Finley (1992) found that sequential models in which bulbs "use up" current were the most common type of model amongst the elementary and middle school teachers whom they studied.

How did Students' Understanding Compare from Pre- Post Measures Depending Upon Intervention Group?

Interview Data:

The importance of the interview data is that it offers a picture of whether students underwent conceptual change in the models that they brought to analyzing the simple circuit. It offered an in-depth, scaffolded opportunity for students to reveal their best thinking. The highest level model that was taught to the fourth graders was the cyclic simultaneous model. The interview data provides a picture of how many students achieved a deep understanding of that model and could apply it to various instances on their own.

A one-way analysis of variance (ANOVA) was conducted on students' pre-interview scores by group to ascertain that there were no significant starting differences between the groups ($\underline{F}(2, 26) = .15$, $\underline{p} = .86$). However, a Tukey Kramer HSD multiple comparisons t-test was conducted to assess whether there were differences on students' post-interviews by group. It revealed that the causal models group significantly outperformed the control group ($\underline{p} < .05$) and the activities only group ($\underline{p} < .05$). No significant differences were found between the control group and the activities only intervention group. Table 1 (and accompanying figure) shows the means and standard deviations for each group.

Table 1. Means and Standard Deviations Revealing Significant Differences between Students' Post-Interviews By Intervention Condition.

[Insert Table 1 about here.]

A similar analysis was conducted considering gain scores. This analysis revealed significant differences between the causal models and the control group subjects ($p < .05$). No other significant differences were found. The trends are similar to those found with post-test scores. The ceiling effects–that nearly all of the students in the causal models group achieved the highest model taught and no other gains were possible–may explain the lack of significant differences between the causal models and activities only groups on gain scores.

All of the students in the causal models group held cyclic models and all but one held cyclic simultaneous models on the post-interview. Figure 7 shows how many students in each intervention condition held each model type on the post-test.

Figure 7. Number of Students Using Each Model Type on Post-Interview by Intervention Condition (n= 27)

[Insert Figure 7. about here.]

Did Students' Achievement Level Affect Their Ability To Gain From the Causal Models?

A simple regression analysis was conducted plotting pre-interview scores against achievement level. Achievement level was a significant predictor of students' pre-interview scores (F (2, 27) = 6.23, p = .007) with the lowest level students doing the least well. Table 2 represents the mean model score for students at each achievement level. This is certainly not surprising and would be expected.

Table 2. Pre-Interview Scores by Achievement Level

Level	Mean	Standard Error
Low	0.83	0.144782
Medium	1.22	0.144782
High	1.55	0.144782

A multiple regression analysis plotting group and achievement level against post-interview scores shows that intervention group (F (2, 27) = 11.2, p = .0004) is a significant predictor of post-interview performance but that achievement level is not (F (2, 27) = 2.3, p = .1238). No significant interactions between group and achievement level were found and it would be unlikely to find such an effect with such small cell sizes. However, the following graph (Figure 8) shows the performance of low achievers within each group on post-interview scores. The graph suggests that the causal models intervention benefitted all of the students in the group regardless of achievement level.

[Insert Figure 8. about here.]

The overall results from the interview data suggest that students in the causal models intervention made the greatest gains in the type of model that they used to explain electrical circuits. It appears that by some measures (post-interview scores), discussing the causal models led to significant gains over the mere presentation of the intermediate conceptual models through activities designed to teach them. Based on post-interview measures or gain scores, students in the causal models group outperformed students in the control group. How does this relate to how students performed on the inventory of scientific knowledge about electrical circuits? We consider this data next.

Inventory

The importance of the inventory was that it showed whether students still held typical misconceptions that they brought to the unit, such as the idea that the circuit is initially empty or that current is not conserved and that bulbs in a series will get progressively dimmer the further away from the battery they are. It also showed students could apply the models that they had learned to reasoning about the circuit beyond what they had directly been taught. The inventory asked students to reason about what would happen with series and parallel circuits, for instance, and to consider the relationship between voltage, resistance, and current.

A one-way analysis of variance (ANOVA) by intervention condition was conducted on the pre-inventory scores to make certain that there were no significant differences between the groups at the outset of the study (F (2, 63) = .0356, p = .9651). No significant starting differences were found. However, a Tukey HSD multiple comparisons t test revealed significant differences between intervention condition on students' post-test scores. (See Table 3 and accompanying figure.) The Causal Models group significantly outperformed the control group and the activities only group by approximately one standard deviation. There were no significant differences between the control group and the activities only group.

[Insert Table 3. about here.]

Similar results were found using students' inventory gain scores. Students in the Causal Models Group gained on average 5.6 points, one standard deviation above the Control Group at 2.9 points and close to one standard deviation above the Activities Only group at 3.3 points.

What did the students have to say about learning to think about causality differently?

Following the administration of the post-inventory and the post-interview session, we interviewed students in the causal models group in an effort to understand through an interview context what they found difficult about learning the cyclic simultaneous model of causality for electrical circuits. Here is a sampling of some of the kinds of difficulties that have arisen out of students' comments following the post-interview and in class discussions.

A number of students said that simultaneous cyclic causality is difficult to talk about without resorting to a sequential explanation. Students said that they could picture it but that they found it hard to explain. A number of students said that the bicycle chain analogy made sense to them. As Ben (not his real name) said "Its kind of hard to think about. The way we have to learn it is like what's making what happen so you think of it in a line, so then its really hard to think that its happening all at once."

Other students commented that thinking of something as both a cause and an effect was a new idea to them. When the model was introduced in class, Ling (not her real name) commented that "How can something be a cause and an effect? That's kinda weird" Afterwards when all of the students were moving their desks out of the discussion circle, Ling noticed that her desk was stuck because two other students' desk were stuck and this was due to her classmates having put their desks back before the three of them moved theirs out of the corner. She laughed and said, "Now that's complicated cause and effect. Shane's desk is the cause of my desk not being able to move, but her desk is the effect of Ryan's desk being stuck and that's cause everybody moved their desks before we did. Its causes and effects at the same time!"

The models used in the first year were not dynamic models and this impacted the students' ability to visualize them well. As one student commented when asked whether there was anything she found hard about learning the cyclic causal stories: "The part about...you can't really see in your mind about the "all going at once" but it all is. You have to like see it like the diagram and then you can really tell that it was all going around at once" [Subject #35]. This year we have developed dynamic models to help students visualize the differences between the models.

One of the challenges of teaching such models will be to develop an accessible vocabulary for talking about the models with different age students and an effective pedagogy for best teaching them and addressing the conceptual difficulties students have.

One Student's Progression Through the Causal Models

To give a greater sense of what the process of coming to understand the different causal models was like for the students, we'll trace the progression of understanding of a student named Tom (not his real name), an eighth grade student, as he grappled with and achieved new understandings.

Tom began by offering a double linear attraction model on his pre-interview.

> I: Why does that work to light the light bulb?
> T: Because it needs to get both the pluses and the minuses from the battery. They attract to each other go into the bulb.
> I: What happens then?
> T: I guess they lose their charge and balance out again.

When analyzing a series circuit, Tom used the idea of traveling protons and electrons and said that he believed both bulbs would light at the same time because it would take the negatives as long to get to the one bulb as it would take the positives to get to the other.

Some students in class had linear models and some held cyclic models. The students discussed the difference between linear and cyclic types of causality. Could they create arguments for which one might be operating in this case? A number of students argued against the double linear model because it required that protons move and as the students recalled from their matter unit, protons are relatively heavier than electrons and only in rare instances, move. At that point, Tom changed his model. He had the following reflection:

> T: My first idea made sense because of what we learned about protons and electrons being attracted in static electricity. But what I didn't think about is that there is more than one way

> for them to be attracted. The cyclic model has the electrons going to the protons and getting away from the electrons.

At this point, Tom seemed to hold a cyclic sequential model. He switched his argument about the series circuits and said that the one that was closer to the negative side would light up first.

Most students in the class held cyclic sequential models and it was not entirely clear that the teacher didn't. So the researchers introduced the idea of cyclic simultaneous causality and contrasted it to the cyclic sequential model. A number of students commented that the cyclic simultaneous model made sense in part because the lights came on as soon as you hooked the wire up, you didn't have to wait for electrons to get to the light bulb. Another student argued that you still wouldn't know the difference, the electricity could just speed up if it needed to. This launched an animated discussion about how electrons could possibly "know" to speed up and whether they had forethought. The students let go of this when the teacher asked, "What are wires made of?" and one student made the connection that there has to be some electrons along the wire because it is made up of atoms. Tom did not say a lot during this conversation, he just looked thoughtful and seemed to be taking it all in. Afterwards, he said:

> T: At the end, the cyclic all at once model [simultaneous] seemed like it worked better. I still had a hard time picturing it in my head. The idea of a bicycle chain helped. It's hard not to think of it as one step at a time.

On his post-interview, Tom applied the cyclic simultaneous model to simple, series, and parallel circuits. His arguments reflected more of a systemic view of the circuit. For instance:

> I: Why do both bulbs get dimmer in the series circuit?
> T: Well, because if you see the whole thing like a bicycle chain and you think about the resistance where the bulb is, its like the widest bicycle chain that can turn is as wide as the amount of electrons that can move through the bulb and the more bulbs, the harder it is for the whole thing to turn. So there's less current.

As difficult as the cyclic simultaneous model is to visualize, the idea of the bicycle chain seemed to give Tom an image to reason from to think about the relationships between voltage, resistance, and current.

Discussion and Conclusions

The results here suggest the importance of teaching about the nature of causality while teaching about particular instances of causation in helping students move beyond their misconceptions about how electrical circuits work. While the students who learned about the particular instances of causation through activities designed to help them did make some progress, fewer of the students in this group reached the level of the causal model in the scientific explanation offered than in the group that engaged in explicit discussion of the nature of causality.

It is particularly interesting that this explicit level of discussion appeared to help students of all achievement levels across the board. It makes sense that the cognitive load of learning about particular instances of causation and trying to abstract the underlying causality would provide the most difficulty for students who typically struggle. Therefore, making this information explicit might help them. This fits with previous research on metacognition and reflection (White & Frederiksen, 1995). Offering the causal rules explicitly seemed to function as a means to level the playing field. Interestingly, teachers typically believe that lower-achieving students are the least able to benefit from higher order thinking including metacognition (Zohar, n.d).

This work reflects our initial attempts at teaching the causal models and certainly there is much to be figured out about the best ways to teach them and the appropriate age levels at which to do so. Beyond this, there is a great deal to learn about where the conceptual stumbling blocks are for different age groups between the various causal models.

How does this work contribute to our understanding beyond what was already understood based on previous research? It certainly confirms the importance of considering how students think about the nature of causality. Beyond that it shows that impacting students' thinking about the nature of causality impacts their ability to move beyond some of their most basic misconceptions about simple circuits. Finally, by offering teachers a way to organize students' misconceptions so that they are more theory-like--at least in terms of underlying causality–it unifies some of the disparateness of previous research. It certainly can be argued, as di Sessa (1993) has, that such unification should be approached with skepticism. From a very exacting philosophical stance, one certainly might argue about the details of the models presented here. However, from a pedagogical stance, seeking models that consolidate various misconceptions and addressing the inherent conceptual causal leaps, may offer a great deal of leverage in helping students address their misunderstandings and move to more powerful explanatory models.

Others have called for adequate, accessible causal models at intermediate levels to help learners achieve more complex scientific understandings (e.g. White & Frederiksen, 1993) and especially those that "build on intuitive notions of causality and mechanism" (White, 1993, p. 182). We agree on the need for accessible causal models and add that students' intuitive notions may embed expectations about the nature of cause and effect that create difficulties of understanding. Students (and often, teachers) may not be aware of their "causal stance." This research suggests that helping students and teachers address their assumptions and learn to recognize new, more complex forms of causality is a promising avenue towards inducing conceptual change. It promises to significantly and systematically impact students' ability to learn a host of important, complex science topics.

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Figure 6. Number of Students Using Each Model Type on the Pre-Interview by Intervention Condition (n= 27)

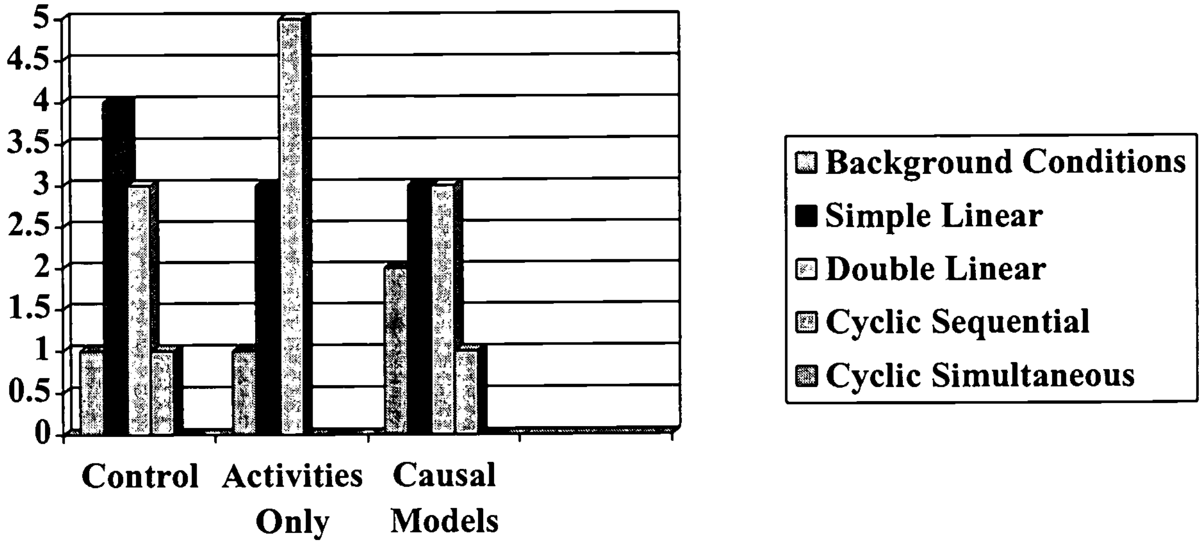
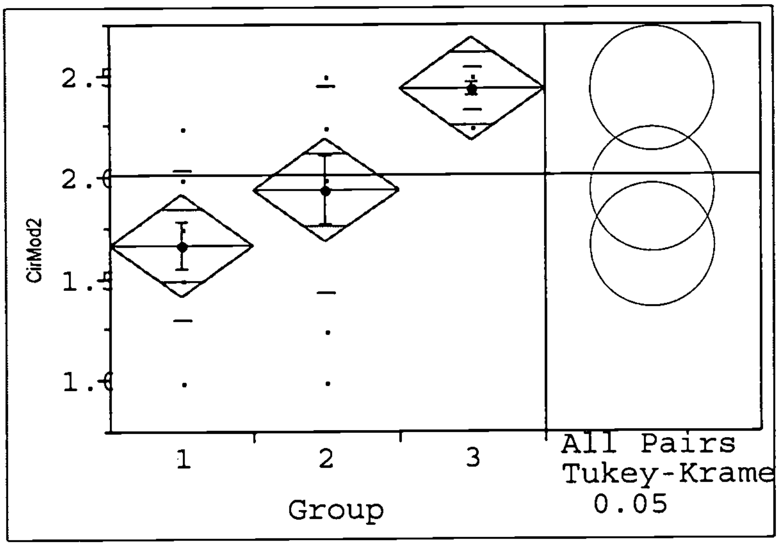


Table 1. Model Level for Analyzing the Circuit on Post-Interview by Group



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
1-Control	9	1.66667	0.375000	0.12500
2-Activities Only	9	1.94444	0.512009	0.17067
3-Causal Models	9	2.44444	0.110240	0.03675

Figure 7. Number of Students Using Each Model Type on Post-Interview by Intervention Condition (n= 27)

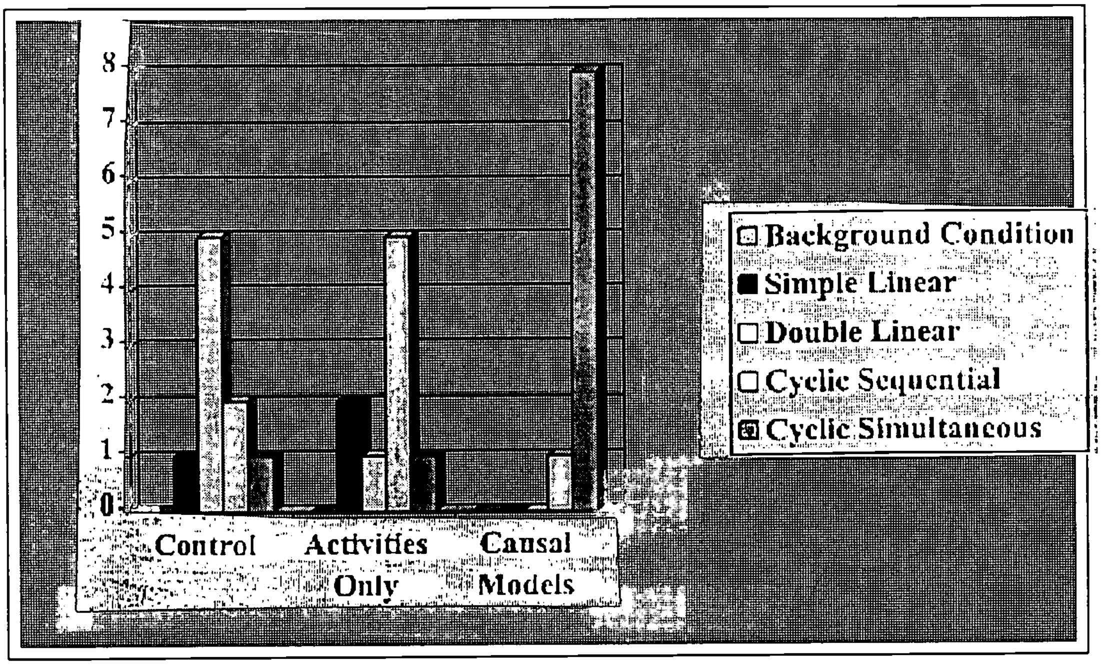
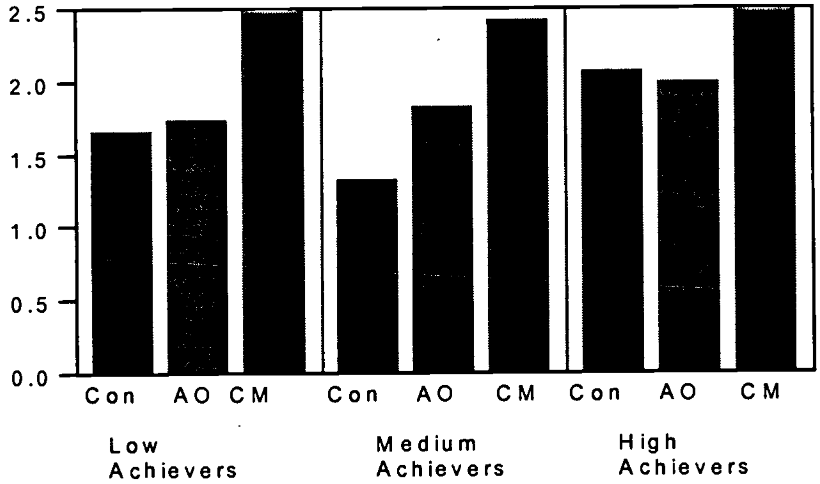
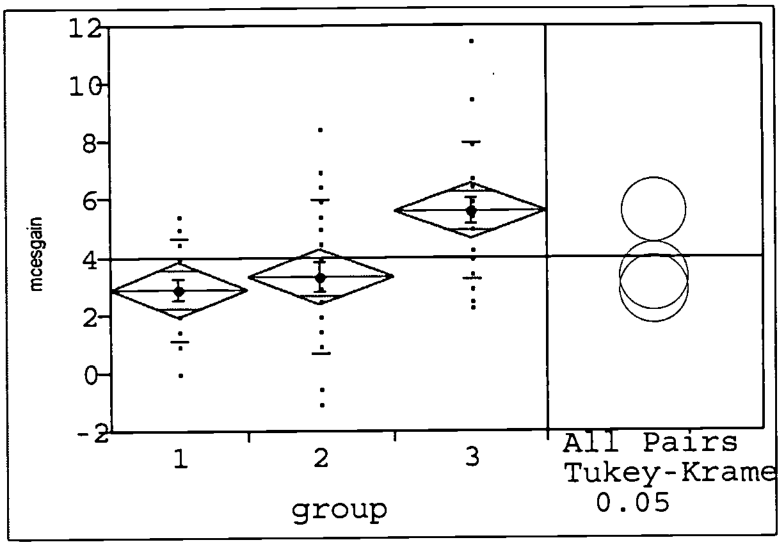


Figure 8. Models on Post-Interview by Group within Achievement Level



*Model Levels:
2.5 = Cyclic Simultaneous
2.0 = Cyclic Sequential
1.5 = Double Linear
1.0 = Simple Linear
0.5 = Background Conditions

Table 3. Inventory Gain Scores by Intervention Condition



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean
1-Control	21	2.88095	1.80904	0.39476
2-Activities Only	22	3.34091	2.70091	0.57584
3-Causal Models	23	5.59478	2.40618	0.50172

NOTICE

Reproduction Basis