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Step-Wise Evolution of Mental Models of Electric Circuits: A "Learning-Aloud" Case Study

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Various methods have been tried for fostering conceptual change in science including the use of analogies, discrepant events, and visual models. In this article we describe an approach to teaching complex models in science that takes a model construction cycle of generation, evaluation, and modification as an organizing framework for thinking about when to use each of the previous strategies. This approach of model evolution uses all of the previous methods as students are led to reassess and revise their model many times in the course of the lessons.

We reported on the case study of a student in a tutoring experiment using this approach in the study of electric circuits. We concentrated on the student's moments of surprise as motivators of conceptual change. Most of these came from discrepant events, but 1 of them appeared to come from the student's own sensed lack of coherence in an intermediate model. In this case study, the teaching method appears to lead to the construction of an explanatory model that is fairly deeply understood by the student in the sense that it can generate predictions and coherent explanations of a complex system in a transfer problem.

Some of our conclusions and hypotheses generated with respect to learning processes are as follows: (a) Discrepant events produced reactions of surprise and were eventually followed by model revisions, leading us to hypothesize a motivating and

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guiding role for these events; (b) the subject was able to map and apply an air pressure analogy used for electric potential and continued to exhibit traces of it through the posttest interview; (c) the subject's spontaneous use of similar depictive hand motions during the instruction and during the posttest provides initial evidence that the instruction fostered development of dynamic mental models, such as those of fluid-like flows caused by pressure differences, that can generate new mental simulations for understanding relatively difficult transfer problems. This leads us to describe the core of her new knowledge as explanatory models at an intermediate level of generality that allow her to run imagistic simulations and to hypothesize a "transfer of runnability" from the analog conception to the model in this case; (d) we hypothesize that the process underlying model generations and revisions was 1 of scaffolded abductive knowledge construction rather than induction or deduction; that evaluation and revision cycles can make up for the conjectural nature of individual abductions; and that engagement and comprehension in the cycle was fostered by small step sizes for revisions from using multiple "small" discrepant events and analogies built into the lessons.

In this article, we report on the case study of a student in a tutoring experiment on electric circuits. We concentrate on the role of analogies, discrepant events, and the student's moments of surprise as motivators of conceptual change. Our primary purpose is to generate theoretical hypotheses concerning the subject's learning processes and resultant knowledge structures. These, in turn, should allow us to articulate clearer and more detailed hypotheses about effective teaching strategies.

The term *conceptual change* has been used in a variety of ways. Thagard (1992) described a spectrum of possible degrees of conceptual change, from changes in relatively surface level details, or small revisions, to radical shifts in core concepts. Here we will refer to conceptual change as a type of learning where significant new cognitive structure is created—a change that is structural or relational in character rather than a change in surface features. Depending on the case, this might mean the construction of a significant new structure or a significant modification of an old structure.

During the 1970s a number of experiments were carried out that aimed to foster conceptual change by using surprising or discrepant events —observable phenomena that the investigators thought would conflict with student's preconceptions and thereby foster conceptual change (Champagne, Klopfer, & Gunstone, 1982). These methods were only partially successful. A criticism of this work voiced by some was that while it may have provided motivation for conceptual change, it left a gap in that it did not provide sufficient strategies for how the new conception was to be built up after the limitations of the old conception were exposed.

More recently, a number of investigators have concentrated on the "building up" side of conceptual change through the use of analogies in instruction (see reviews by Dagher, 1995; Duit, 1991). Most of these rely on the idea that certain critical causal relations can be transferred from the analogous case to the topic at hand, thereby providing an efficient and effective means to building the new conception. In the area of electricity, Johsua and Dupin (1987) found that, whereas discrepant events were largely ineffective on their own in overcoming alternative conceptions in 12 and 14 year olds about varying currents in a single-loop electric circuit, combining them with a "circular train on the tracks" analogy that emphasized equal currents everywhere produced greater success. Gentner and Gentner (1983) taught two groups of students using two different qualitative analog models for simple electric circuits: "flowing waters" (a fluid model for currents) and "teeming crowds" (a particle model). Students tended to answer posttest questions differently depending on which model they had used, showing that the analogy did in fact affect the model that they developed. However, neither group did as well on the posttest as one would hope, probably due to the limitations of these oversimplified models. Single analogies are sometimes criticized as being too different from, or not as complex as, the targeted conception, so that their usefulness is limited.

A few recent approaches to teaching electric circuits such as those developed by Gutwill, Frederiksen, and Ranney (1992), Niedderer and Goldberg (1996), Steinberg et al. (2000), and White (1989) attempted to overcome this last difficulty by developing more refined models that go beyond a single analogy. White and Frederiksen suggested that the flexible use of multiple models held simultaneously was important to development of expertise in the area of electric circuits. They used two animated computer simulations to represent DC circuits at a microscopic electron flow level as well as a macroscopic current or voltage level. They believed that learning from a combination of these two levels fostered abstract construction and led to deeper conceptual understanding.

General models of tutoring for understanding have been described by Collins and Stevens (1983), Merril, Reiser, and Ranney (1992) and White and Frederiksen (1986). The latter article used the term *model evolution* to describe the incremental growth in sophistication of a student's model. Clement (1994b) and diSessa (1983) described the growth of knowledge in physics as the evolution of intuition, making the point that even many expert concepts can have their origins in everyday physical intuitions.

As illustrated by the Gentner and Gentner and the White and Fredericksen articles cited previously, another recent theme in conceptual change research is a focus on mental models as having central importance, in the form of target conceptions that the teacher hopes to develop (Karplus, 1969; Lewis, Stern, & Linn, 1993; Mayer, 1989; Niedderer & Goldberg, 1996; Wiser, 1992). Many of these authors have also been interested in taking students' alternative conceptions into account and in using analogies as a key element in developing mental models. However, the distinction between an analogy and a model has not always been clear, nor has the strategy for progressing from an initial rough analogy to a more refined mental model. Most previous articles also do not address the issue of whether it is desirable to construct a model that can generate imageable mental simulations.

PURPOSES

In this article we attempt to develop concepts and diagramming tools for describing learning processes involved in model construction. We try to make a clear distinction between individual analogies and the overall target model they help to develop. Multiple analogies are used to help construct different aspects of the final model (Spiro, Feltovich, Coulson, & Anderson, 1989). In addition, there is the question of whether analogies and discrepant events are two separate strategies to be used for different types of learning situations, or whether there are strategies for using them in a coordinated way. We also ask whether there are advantages for developing mental models that appear to generate imageable simulations.

METHOD

The tutoring study to be discussed in this article uses teaching strategies from an electricity curriculum called CASTLE, developed by a team of teachers and researchers led by Steinberg (Steinberg, 1983, 1985, 1987; Steinberg et al., 2000; Steinberg & Wainwright, 1993), which uses discrepant events and analogies in concert to foster step-wise model construction. Preliminary results have suggested that the curriculum is more effective than other approaches in developing major concepts (see Appendix). However, because multiple strategies have been used in this and other studies mentioned previously, it is hard to draw conclusions about specific learning processes without tracking students' reasoning during an extended learning process. Attempts to track learning processes at this level of detail in groups of students have been frustrating for us because we do not hear enough from each student to follow the process without large gaps. We will attempt to do this in this study by focusing on the learning of a single student who was asked to think aloud as she learned. Although questions in the previous paragraph cannot be answered definitively for all students on the basis of a case study, such studies can be an important source for generating grounded hypotheses about learning processes that have a substantial initial level of plausibility and that are worth investigating in larger samples (Clement, 2000). As Anzai and Simon (1979) put it,

> It may be objected that a general psychological theory cannot be supported by a single case. One swallow does not make a summer, but one swallow does prove the existence of swallows. And the careful dissection of even one swallow may provide a great deal of reliable information about swallow anatomy. (p. 136)

Thus, this article concentrates on obtaining more detailed descriptions of cognitive learning processes. Certainly these will need to be integrated with social learning processes for successful application to the classroom. However, we believe that by developing terms for describing learning processes in tutoring, we can gain a valuable conceptual vocabulary for thinking about cognitive goals and methods in group instruction, even though those methods will need to be supplemented and adapted for use in the classroom.

Teaching Method

Conventional approaches to electricity instruction in physics courses start with electrostatics and quickly introduce a *mathematical* description of distant action based on two kinds of charge. The potential difference concept, which is key to effective analysis of electric circuits, is defined mathematically—typically in terms of an integral over a vector function.

Physicists and engineers are generally agreed that effective reasoning about electric circuits requires a robust conception of electric potential. However, research in the 1980s found that electric potential typically remains unlearned after instruction (Closset, 1983; Cohen, Eylon, & Ganiel, 1983; Duit, Jung, & von Rhoneck, 1985). Students reason exclusively with current and resistance when possible, and when asked explicit questions about potential difference they confuse the concept with current. They use sequential reasoning—the idea that a downstream component cannot influence an upstream event—as a substitute for causal reasoning.

The approach we shall describe here takes pains to develop a strong *qualitative* conception of electric potential in conducting matter, based on an analogy to pressure in compressed air that is compelling to most students, before introducing distant action and mathematical representation. This article focuses on the first four steps of model construction in tutoring sessions that used the concept of "pressure" in a compressible electric fluid—a concrete prototype conception of electric potential in conducting matter—as the causal agent of current propulsion in circuits.[1] The approach starts with hands-on investigation of simple electric circuits with steady-state bulb lighting, and then of circuits that also include capacitors and transient bulb lighting. Discussion of issues in the larger curriculum can be found in the articles by Steinberg in the references.

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[1] This article does not deal with the entire CASTLE curriculum, which also includes distant action and two kinds of charge; scalar and vector fields in space; atoms, electrons, and magnetic effects; semiconductor devices and alternating current; and energy transfer and storage.

The lessons begin with simple observations and analogies, and take students through a developmental sequence of more and more expert-like qualitative models of electric circuits. The lessons begin with discussion of the most common alternative models used spontaneously by students (such as "electricity sent out from both sides of a battery"), which are largely in conflict with accepted theory. Stimulated by a series of discrepant observations followed by group discussions, these models are criticized and revised.

The students are eventually led to adopt a model for electric potential in conducting matter that starts from an analogy to *pressure in a compressible fluid*, and this model is developed carefully to avoid pitfalls of the analogy. Eventually, additional discrepant events are introduced that reveal distant-action phenomena and foster evolving construction of a field-in-space model, but this development is beyond the scope of this article. This approach assumes that students must pass through a series of more and more complex and refined models, rather than counting on a single initial analogy to carry all of the weight, to achieve understanding. Thus, it asks students to investigate the limitations of each modeling step they achieve: They criticize and test aspects of the model at each stage of development (e.g., the idea that "only batteries can 'push' on charge, not capacitors"), and improve the model where necessary. This is a process that emulates model construction in the thinking of scientists (Clement, 1989; Darden, 1991; Nersessian, 1990).

Research Method

The data base for this article is a set of tutoring interviews with a student whom we shall call Susan who was 16 years old and had completed her junior year in high school. Susan was one of several students who volunteered to participate in science tutoring sessions to be held during the summer. Her teachers characterized her as having previous average, but not superior, ability in science. Susan had taken a course in chemistry, but had not yet taken a course in physics. Susan's tutor was an experienced high school physics teacher who had been a member of the development team for the CASTLE curriculum.

In Susan's first session, she was asked to think aloud as she completed a pretest on electric circuits. She did this again with an identical posttest in her last session. The 5 intervening tutoring sessions were spread over a period of 2 weeks and lasted from 60 to 120 min each. Susan was also assigned a homework problem after most of these sessions. During the tutoring, Susan was asked to think aloud as she set up and observed experiments with circuits, constructed explanations for events, solved problems, reacted to the tutor's comments, and completed color coding for "electric pressure" (potential) values in circuit diagrams.

All sessions were videotaped with a dual camera, picture-in-picture system allowing us to record facial expressions and hand movements of the student and the tutor, as well as close-up images of drawings and manipulations of apparatus. Sections of the tapes were reviewed by both authors, and an initial outline was created jointly in which major learning episodes were identified. These episodes were then transcribed for more detailed analysis. Our analysis was guided by several questions:

- Was there evidence that Susan's ideas had gone through one or more conceptual changes during and after the tutoring? Here we looked not only for correct predictions as answers to problems, but also for Susan's ability to give coherent explanations in her own words about how circuits work.
- What was the form of Susan's new understanding—the form of the knowledge she had acquired? Here we did not restrict ourselves to looking at verbal statements, but also sought evidence from hand motions to provide clues as to whether her new understanding was based on mental models capable of generating imagistic simulations.
- What learning processes were responsible for Susan's conceptual change? Here our analysis led us to focus special attention on the effect of discrepant events and analogies.

We considered this to be a form of generative research, because our purpose was to generate grounded hypotheses concerning key learning processes taking place during the sessions and the resulting understandings developed by the student. Therefore, we used a form of interpretive analysis, leading to the development of cognitive models of certain learning and understanding processes (Clement, 2000). As the authors worked jointly to characterize and debate the form of these models, the models were improved over time in cycles of generation, evaluation, and modification, with observation patterns suggesting cognitive processes, which in turn suggested new elements to look for in the transcript. Models of processes were checked and rechecked against the transcript to suggest alternative interpretations and to criticize and further refine the models. Multiple sources of evidence from different lines of the transcript were sought to provide triangulated support for our final models wherever possible.

In the first half of this article, we describe Susan's major model-building episodes from the tutoring sessions, using excerpts from her transcript. These focus on four moments of surprise where she made unanticipated observations of circuit behavior or of gaps in her own knowledge. In the second half of the article, we discuss each of the previous questions from two perspectives: (a) a summary of findings about the subject's learning that are grounded in multiple observations from the protocol, and (b) more general hypotheses comprising elements of a theory of learning and instruction that can explain the events in the teaching strategy used.

CASE STUDY OF CONCEPTUAL CHANGE EPISODES

Pretest

Susan's pretest revealed that she had very little academic knowledge of electric circuits. In simple circuits with a battery and one or two bulbs, she felt that electricity must flow somehow from a battery to a bulb, but was unsure about the path it would take. On more difficult questions she said she had no idea about what would happen, and the instructor reassured her that this was alright and not unusual.

Background to the Protocol

We will now describe four learning episodes initiated by transient bulb lighting events to which Susan reacted with strong expressions of surprise. The transcripts presented from this 5 day intervention are necessarily only a small piece of the entire intervention. Prior to these episodes, Susan had learned in hands-on experiences: (a) how to hook up simple circuits of flashlight batteries and light bulbs, and (b) how to find out whether materials used in circuits are conductors or insulators. When asked what she thought might be happening in the wires during bulb lighting, she began talking about *something moving* through the wires from the battery to the lighted bulbs. At first Susan talked about "positive and negative currents" moving out from both the battery terminals labeled "+" and "–". (We believe the predisposition to think this way derived from a chemistry course she had recently taken.) When she seemed blocked by a morass of questions associated with currents flowing in opposite directions to two bulbs connected in series, the tutor suggested trying the simpler idea that bulb lighting is associated with something moving in a *single* direction in each wire. The tutor showed Susan how to use a compass placed under each wire to determine (relative) directions of movement in the wires, and recommended using the name "charge" for whatever-it-is that's moving in the wires. However, at this point Susan still appeared to have little knowledge of what caused these movements or their magnitude, and had no knowledge of the concept of electric potential. We first describe the set of conceptions that the tutor hoped the student would be able to learn during this session. What makes dealing with electric circuits difficult is the idea of a causal agent (electric potential) in the wires.

Target Concepts for Susan's Tutoring Interviews

Wires that connect a battery to a glowing bulb were regarded by Susan from the beginning as paths along which *something is moving*. Susan's tutoring interviews were designed to help her use this productive idea to build a model of the role played by these wires in the hidden *mechanism of propulsion*. This involves constructing the following conceptions:

- A wire contains a *fluid-like substance* that will be called "charge." Charge is always present in every wire, whether at rest or in motion.
- This fluid is compressible, and has a *pressure-like property* that will be called "electric pressure." It is the causal agent that makes charge move, and its magnitude depends on the degree of charge compression.
- A bulb lights when charge is driven through it, from a connecting wire where the electric pressure is HIGH due to charge compression and into a wire where the electric pressure is LOW due to charge depletion.
- A battery moves charge internally from its (–) to (+) terminal, causing depletion and LOW pressure in the (–) terminal and attached wires together with compression and HIGH pressure in the (+) terminal and attached wires.

The "electric pressure" concept has complex contextual associations in circuits where multiple bulbs require wires that do not touch the battery. Pressure magnitudes in such wires are determined by a *dynamical process in the circuit*. The simplest case is two nonidentical bulbs connected in series with a battery:

- Pressure in the wire joining the two bulbs is raised by inflow through the upstream bulb and lowered by outflow through the downstream bulb.
- Unequal flow rates through the bulbs means unequal inflow and outflow for the wire joining them and a changing pressure magnitude in the wire.
- The result is opposite changes of pressure differences across the bulbs, which makes flow rates through the bulbs more and more nearly equal.

The term *pressure* is used here to connote a compressed fluid's *effort to push itself out* of a container. Experiences as primitive as blowing up and releasing a balloon may provide an initial basis for this idea. Electric pressure is a concrete prototype conception of "electric potential" that allows reasoning with reduced abstraction, but is restricted to conducting matter. (The force per area exerted by a fluid on a surface is also called "pressure," but this technical ratio concept is not the intended meaning.)

The Trajectory of Susan's Conceptual Change

Besides the useful idea that something is moving in the wires connecting a battery to a lit bulb, Susan initially held two other beliefs that are at odds with the target model:

1. The battery is the *only source* of what's moving along the wires.

2. The battery is the *only agent* that can make the movement occur.

We will call this pair of ideas the "sending-out" model of the battery. Conceptual change along a productive path would be possible only if Susan could be led to revise the sending-out model in favor of the following:

1. What's moving is a fluid originating in wires as well as batteries.
2. What's making the fluid move is pressure differences in the fluid.

Since fluid being in the wires at all times is a precondition for pressure being in the wires at all times, the tutor provided an investigation that led to Revision (1) before an investigation that led to Revision (2).

In this article we describe how Susan arrived at the target model through a sequence of four cycles of model generation, evaluation, and modification (or revision, here used synonymously with modification). Her conceptual change was stimulated by observing the effects of fluid flows in circuits with batteries, light bulbs, and capacitors. During each cycle, Susan abandoned a conception that blocked understanding and replaced it with an idea on which further model building is based, as shown in Table 1.

A broad definition for the term *model* is a simplified, general, and usually idealized representation that can predict or account for a system's behavior. However, we will describe the previous trajectory as a sequence of increasingly sophisticated *explanatory models*. This is a special kind of model that is explanatory in the sense that it represents hidden, unobserved mechanisms that can be used to explain observable properties of circuits. As articulated by philosophers and historians of science, such as Harre (1972), this is a fundamentally different type of knowledge than a condensed summary of a pattern of observations. It involves thinking about

TABLE 1

Cycle	*Preconception*	*Modification*
1	The fluid moving in a circuit comes only from the battery.	This fluid originates also in all metal parts of a circuit.
2	The battery is the only agent that can make the fluid move.	Compression can create high pressure that pushes fluid out.
3	Normal pressure can't push fluid out of a capacitor plate.	Normal pressure can push into low in the (–) battery terminal.
4	Rate of inflow to a wire must always equal rate of outflow.	Inflow can differ from outflow and alter pressure in the wire.

the system in terms of hidden material elements that are thought to be working as causal or functional agents within the system. In this article, *model* will be used in this narrower way to refer to explanatory models.

In the tutoring sessions, the student and tutor each take different degrees of initiative in different episodes in constructing these new models together in a joint effort, but the tutor rarely presents Susan with a completed model directly. In what follows we will use terms like "Susan constructed model X" to mean that she played an important role in initiating or completing an explanatory model; we do not mean necessarily that she did this alone or without help.

Analysis of Susan's Protocol

Surprises. The circuit that generated Susan's first surprise is shown in Figure 1. All earlier investigations had used the 2-bulb circuit shown in Figure 1 *without the capacitor.* Before introducing the circuit in Figure 1, the tutor described the layered conductor-insulator-conductor architecture of a capacitor: Two conducting sheets of metal (called "plates") are separated by an insulating sheet sandwiched between them so that there is *no direct contact* between the plates. We begin quoting from the videotape at this point in the tutoring interview.

Surprise #1: A bulb lights downstream from a capacitor connected in a circuit with a battery pack of 3-D cells.

1.1. TUTOR "I'm gonna put the capacitor in the middle" (between the bulbs in Figure 1).

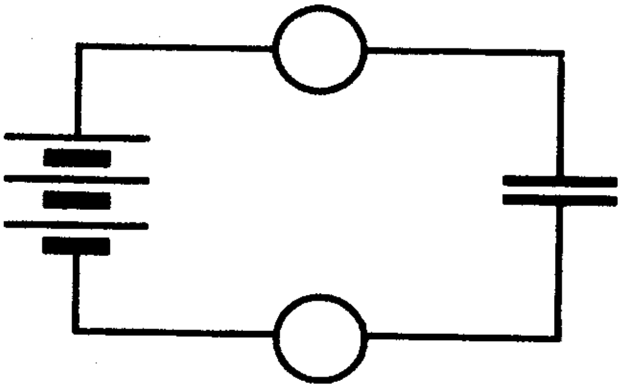

FIGURE 1 Capacitor charging.

1.2. SUSAN "...I don't see how it can light the bulbs."
1.3. TUTOR "Tell me why the bulbs can't light."
1.4. SUSAN "Because they're both connected to different thin pieces of metal that never touch" (the capacitor plates). "And the current is just gonna stop."
1.5. TUTOR "As you said, there's an insulator in the middle here (between the plates)... Hook them up. Make them do nothing!!"

Susan completed the hookup of the circuit in Figure 1, and was surprised to observe bulb lighting (which lasted about 1/2 sec).

1.6. SUSAN "Huh-ho. Wait a minute."

We take her surprise as evidence for some internal dissonance or felt incongruity with her expectations. At the tutor's suggestion, Susan then used the compass to investigate the direction of movement in each wire during charging. The tutor inquired about her inferences from this new information:

1.7. TUTOR "Where did the charge come from that made this [top] bulb light?"
1.8. SUSAN "It came from the red [top] end of the battery. But I don't understand how this [bottom] bulb could light too."

The first sentence in line 1.8 suggests that Susan interprets lighting of the top bulb as due to arrival of charge sent out by the battery. Additional evidence for a sending-out model of the battery can be found in scattered remarks made later on about the top end of the battery being an "initiator of current." At this stage of development of Susan's ideas, the battery appears to be the only place where the moving charge originates.

The idea in line 1.4—that the insulating layer in the capacitor prevents flow altogether—appears later to have been dropped in favor of a *letting-in* model of the top capacitor plate. Evidence for this appears in later remarks about the top plate "taking more in" when an extra battery is added in the circuit.

The second sentence in line 1.8 suggests that Susan finds the lighting of the bottom bulb much more puzzling than the lighting of the top bulb. Here we have evidence for Susan evaluating and sensing a gap in her model—realizing that she cannot explain why the bottom bulb lights. The tutor now asks for her ideas about this phenomenon:

1.9. TUTOR "Which way is the current moving through this [bottom] bulb?"

1.10. SUSAN "It should be coming that way" (from above the bottom bulb). "I mean it should be coming from where it can't be coming from."
1.11. TUTOR "Did it come from over here?" (from somewhere above the capacitor).
1.12. SUSAN "No. It came from the capacitor. So it must come from one end of the capacitor?"
1.13. TUTOR "Absolutely. Not only can you get charges out of a battery. You can also get charges out of an ordinary piece of metal."

Line 1.10 suggests an effort by Susan to further evaluate and characterize the nature of the gap in her model: "It should be coming from where it can't be coming from." Her model is based on ideas of,

- Battery as the *sole source* of what's moving.
- Movement in the *same direction* everywhere.

Line 1.12 suggests an emerging realization that charge moving through the bottom bulb must originate *in the bottom capacitor plate*. This was the first step in moving Susan away from her initial belief that what's moving in a circuit originates exclusively in batteries. The intent of the previous sequence is to help her accept that the moving charge is a normal constituent, not only of batteries, but also of the aluminum foil of which the capacitor plates are made.

In response to further questioning by the tutor, Susan moved steadily toward a revised model that generalizes this inference to include all of the conducting parts of circuit:

1.14. TUTOR "Where does the very first bit of charge that makes the filament light [from the bottom bulb] come from?"
1.15. SUSAN "I guess I'd say the tip of the bulb."
1.16. TUTOR "Can you show me where that is on this drawing?"
1.17. (Points to the bead of silvery metal at the tip of the bulb's screw base.)

She went on to agree that mobile charge should also be a normal constituent of the metal connecting wires and of the metal tip of a ball point pen. The implicit metaphor here is that capacitor plates and wires are containers of mobile charge—and moreover that these containers are never empty, even when they are not connected to a battery. Of course this is a partial model. It remains to be seen whether it can be modified and elaborated further.

To summarize, Susan's surprise has been interpreted as indicating a level of cognitive dissonance that helps initiate a change in her model. The limited number of places in the circuit where charge could originate have helped to focus the construction of a new view of circuit elements as containers of mobile charge. Readers who wish to place this episode in the complete sequence of four episodes may look ahead to Figures 7 and 8.

Surprise #2: Charge moves back out of the top plate after the battery is removed and wires are reconnected. Removing the battery and connecting the wires that were attached to it initiates a new round of transient bulb lighting. Susan used a compass to find out the direction of movement in each wire during capacitor discharging. She was surprised to discover the charge that had moved along path A in Figure 2a from the battery into the top capacitor plate during charging was now *coming back out*, moving along path C in Figure 2b:

2.1. SUSAN "Once you take it [the circuit] apart, you're eliminating the battery pack. And I was thinking why the current is gonna move in the other direction."
2.2. "There's no place where the charge originates ...to get it to go in the other direction."

Here we have evidence for Susan sensing another gap in her model—where in line 2.1 she sees no causal reason for charge to move back out of the top capacitor plate. In line 2.2 she seems troubled by the absence of any agent that can make the charge move.

The tutor exploited Susan's emerging need for a causal agent to introduce a potentially useful analogy:

2.3. TUTOR "Now I'm going to talk about something completely different, which is going to seem to be unconnected..."
2.4. TUTOR "I would like you to think about an automobile tire."
2.5. "What happens if we put a nail into it?"
2.6. SUSAN "Then you're going to allow an escape for the air."

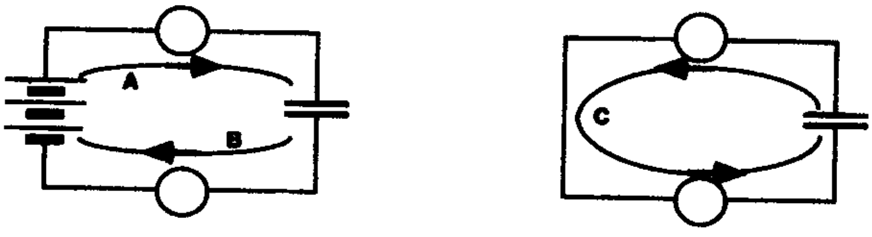

FIGURE 2 2a: Capacitor charging; 2b: Capacitor discharging.

2.7. TUTOR "Why does the air escape?"
2.8. SUSAN "Because you've got the great pressurized air inside of your tire."
2.9. "The air is gonna want to move to an area where there's less pressure."
2.10. TUTOR "Tell me about the pressure inside the tire and the pressure outside the tire right when the air stops coming out of the hole."
2.11. SUSAN "It's pretty close to even."
2.12. TUTOR "Is the tire empty of air when that happens?"
2.13. SUSAN "No."

Susan appears in line 2.9 to have begun thinking about *pressure* as the causal agent that drives air out of an inflated tire. In line 2.13 she also declares that a tire is *never empty*. This indicated to the tutor that Susan has a useable working knowledge of air pressure in tires that can be used as the base for an analogy.[2] She then begins applying these ideas about a tire containing air to a capacitor plate containing charge:

2.14. SUSAN "Uh, uh. I was just trying to hang onto everything."
2.15. TUTOR "Tell me what you're thinking."
2.16. SUSAN "You're never going to be completely empty of the charge. You're always going to have some charge. Whatever metal, or whatever you have, there's always gonna be some amount there."
2.17. TUTOR "You're on a good track..."

We propose that Susan is now moving toward a conception of charge in a capacitor plate as being like air in a car tire. That is, she was able to map and transfer certain elements of the tire case into the circuit case. This development is spontaneous; it was not prompted directly by the tutor. We suggest it was helped by two earlier experiences: (a) Susan's sense after Surprise #2 that the discharging of a capacitor must be due to a causal agent *internal* to capacitor plates (not associated with the battery), and (b) her realization after Surprise #1 that conducting matter is *never empty* of charge. Line 2.9 shows Susan's grasp of pressure as an internal causal agent for the air-in-a-tire analogy, and lines 2.12 and 2.13 show her grasp of

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[2] (Elsewhere the term *anchoring conception* has been used to refer to such a useful intuitive schema in prior knowledge that students may use in the construction of a model [Clement, Brown, & Zietsman, 1989]). When necessary, we will differentiate between the "analogous case" of the punctured tire and "analog conception" of air pressure that it activates. Meanwhile, we will continue to use the simpler term *analogy* to refer to both of these at once.

the never-empty characteristic of the tire. Line 2.16 spontaneously recalls the never-empty characteristic of charge in conducting matter immediately after the air-in-a-tire discussion. What remains to make the charge–air analogy compelling is to validate the idea that *something like pressure* is the causal agent that makes charge move.

Susan's first step in this direction was to identify the location of the causal agent by a process of elimination:

> 2.18. "The wires aren't necessarily dictating which direction the current is going to move in. It's allowing for that, that charge, that air, whatever, to move and sort of equalize the charge."

The fact that the wires "aren't necessarily dictating which direction the current is going to move in" appears to rule them out as seats of the causal agent Susan is looking for. They are only "allowing for" movement, but not causing it. Presumably that leaves only the capacitor plates as places where the causal agent is to be found.

Susan's second step was to *identify the origin* of the causal agent in the capacitor plates. Apparently she initially identifies this agent only as an ability to "move and sort of equalize the charge." In lines 2.7 to 2.13, however, she has raised to a high level of awareness her intuitive understanding that *pressure* is what makes air move. Moreover, her striking phrase "that charge, that air, whatever" in line 2.18 suggests she has developed a view of the air–charge analogy so compelling that the difference between the two has been reduced to little more than a word choice. It is hardly surprising that a short time later the causal agent that makes charge move is explicitly called "pressure." This usage suggests that Susan has arrived at a compressible fluid-like model with pressure as causal agent.

Susan's third step was to *identify the cause* of the pressure that makes charge move during capacitor discharging. She did this by attributing *active* behavior to excess charge in the top capacitor plate—contrasting sharply with her earlier conception of charge as something that is sent out from the battery and passively let into the top plate. She indicated assent to this idea when expressed by the tutor. However, the best evidence we have for this in her own words is found in a retrospective discussion at the end of the learning sessions, where Susan recalls being struck by *charge accumulations* in the capacitor plates having the ability to influence movement:

> 2.19. "The thing that caught my attention the most was the way the capacitor could change the direction of current based upon the charges it contained in its top and bottom capacitor plates."

The pressure concept emerges clearly when the tutor shifts questioning away from the punctured tire, toward the discharging capacitor:

2.20. TUTOR "Why does this charge move back through these bulbs during discharging? What provokes it?"
2.21. SUSAN "Once you take the battery cell out...you don't necessarily have that pump forcing the air in."
2.22. "And that's sort of like...punching a hole in a tire, or whatever, and letting it go back in the other direction."
2.23. TUTOR "What part is like punching a hole in the tire?"
2.24. SUSAN "Kind of discharging. Connecting two wires so that..."
2.25. TUTOR "Connecting the two wires is like punching a hole in the tire?"
2.26. SUSAN "Yeah..."
2.27. TUTOR "Can you compare this to the pressure story and the tire story?"
2.28. SUSAN "Well, I was just thinking about the high pressure moving, once it's got that room to move—that place to expand—that the pressure is gonna take that path [moves hand over path C in Figure 2b]. I'm thinking that the high pressure is going to move to the low pressure."

The language here suggests that Susan may not have fully separated the idea of pressure, a *condition* in air, from the idea of the air in which pressure occurs. Susan had used language showing this separation earlier in line 2.9 ("The air is gonna want to move to an area where there's less pressure"), and she did so later on in the following exchange with the tutor after Surprise #3 was resolved:

2.29. TUTOR "Can you tell me why air comes out of the tire?"
2.30. SUSAN "Because the air pressure inside the tire is greater than the air pressure outside of the tire, and the air is moving. There's a hole in the tire, so that the pressure is going to force the air out of the tire."

This initially imperfect use of concepts, with concept separation occurring later on, appears several times in the interviews. (Lines 5.7 and 5.8 show the last occurrence, with separation immediately following her introduction.) The pattern is typical for students working with newly formed concepts, and is not necessarily evidence that students are failing to learn the concepts targeted by instruction. It is easy to see why students are attracted to the idea of pressure moving during transient flow: When a tank of compressed air is connected to a car tire, the flow of air from tank to tire produces greater pressure in the tire and leaves less pressure in the tank. This result could be described in everyday language by saying that there has been some net transfer of pressure from the tank to the tire.

Line 2.28 provides evidence that Susan has gone beyond the simple idea that charge is always present in all circuit components, and is now imagining a pressure-like *active* condition in these components that is associated with the amount of charge they contain. She is able to use ideas from the tire analogy and map them onto the circuit to explain the discrepant event she has witnessed (lines 2.18, 2.21–2.30). We hypothesize that the familiar idea of "air pressure" has served as an analog conception and starting point for adding the idea of "electric pressure" to her growing explanatory model of the nonbattery parts of the circuit.

Of course, the charge in a bulb filament is pushed in opposite directions by pressures in two wires connected to the bulb. Only a pressure *difference* in these wires can actually cause movement. This pressure difference is a low-abstraction, visualizable prototype of the potential difference concept used by experts.

Surprise #3: No apparent cause for charge leaving the bottom capacitor plate and going to the battery. Surprises #1 and #2 were *reactions to observations* that led Susan to discover pressure as the causal agent that explains capacitor discharging. In contrast, we propose that Surprise #3 was *generated reflectively*—(a) by Susan's realization that she now had the ability to discover hidden causal agents, (b) by the expectation this raised that there should be an agent of some sort for driving movement along *every* path, and (c) by the fact that she had as yet no idea what the cause of movement along path B in Figure 2a might be.

Susan begins by recognizing that she is using *different* ideas about the *causes* of movement into the capacitor along path A (battery sends out) and out of the capacitor along path C during capacitor discharging (high pressure pushes back out):

> 3.1. "Having those…batteries there is forcing that charge in one direction" (Path A).
> 3.2. "I was just thinking about the high pressure moving … that the pressure is gonna take that path" (Path C).

She is then surprised by the realization that she has no idea about the cause of movement out of the capacitor along path B (downstream from the capacitor) during charging:

> 3.3. "But when you're charging up, you're doing it in two different ways in your head. It just blows me away!" (Paths A and B)
> 3.5. "… still wondering what makes it leave here" (bottom capacitor plate). "… have to have something getting it to the battery" (path B).

We interpret the bemused and awestruck tone of "It just blows me away!" to be a reaction of dissatisfaction that an *unidentified cause* makes the bottom bulb just as bright as an identified powerful cause (the battery) makes the top bulb light.

Finally, Susan appears to articulate concern about conceptual fragmentation and to place on herself a demand for unified causal explanation:

3.6. "This makes complete sense to me" (Paths A and C).
3.7. "But what is gonna make this charge leave here and go to the battery?" (Path B)

Susan seemed stuck at this point, with no unifying idea coming to mind. There were two causal agents—battery and pressure—in prior knowledge, that she might have considered as candidates able to "make this charge leave here and go to the battery." With no battery sending out in path B, downstream from the capacitor, that possibility could be quickly dismissed. Yet, why did she fail to consider pressure as the causal agent?

The tutor surmised that Susan was unable to visualize air being pushed away from a region of *normal* (atmospheric) pressure, because most students have had little opportunity to observe air at normal pressure making anything move—compared to experiences with inflated balloons and tires, where air is pushed away from above-normal pressure. As a way to counter this experiential deprivation and expand the usable domain of the air–charge analogy, the tutor engaged Susan in discussion about what will happen if one pumps the air out of a jelly jar and then punctures the lid of the jar:

3.8. TUTOR "I've got a sealed off jar with no air molecules in it. Tell me about the pressure inside the jar."
3.9. SUSAN "It's very low pressure."
3.10. TUTOR "OK. This is like the nail in the tire. What happens after that hole is punched?
3.11. SUSAN "The air is gonna be sucked in."

The tutor probed to see whether this was a true misconception that might undermine the air analogy, or just an undesirable but harmless mode of expression—and decided that the latter was the case:

3.12. TUTOR "What sucks the air in?"
3.13. SUSAN "...it's just moving to the area of low pressure."

Susan now appears to have accepted the logic of outside air at normal pressure pushing into the region of below-normal pressure inside the jar. To regard this as an analogy for what is happening in path B, Susan would have to imagine a region of below-normal pressure in the bottom terminal of the battery. To make that happen, the battery would have to pump charge out of the bottom terminal—and presumably into the top terminal—as shown by the arrow in Figure 3a, where it would produce below-normal and above-normal pressures, as shown in Figure 3a. Accepting this possibility would mean abandoning the original conception of a battery as a device that sends something out into the circuit, and adopting a revised conception as a device that maintains above- and below-normal pressure values in its and terminals as shown in Figure 3b.

The causes of charge flow in the unified circuit model would then be as follows:

> Along path A—Charge is pushed away from above-normal pressure in the top battery terminal, toward a region of normal pressure in the top capacitor plate.
> Along path B—Charge is pushed away from a region of normal pressure in the bottom capacitor plate, toward below-normal pressure in the bottom battery terminal.

To help Susan visualize and evaluate the proposed battery model revision, the tutor stated that chemical reactions in a battery maintain lower than normal pressure in the bottom terminal, and higher than normal pressure in the top terminal, by moving charge out of the bottom terminal and into the top terminal. When the tutor asked, "Am I talking through this too fast?" Susan replied "Nope." A follow-up discussion clarified the issues of pressure in wires that touch the battery terminals, pressure in a wire between two lit bulbs, and pressure in the plates of a capacitor between the bulbs. In this discussion, the tutor introduced the following color code for designating relative pressure values in the metal parts of circuits:

RED > ORANGE > YELLOW > GREEN > BLUE
highest "normal" lowest

- Yellow represents "normal" pressure, due to a "normal" amount of charge.
- Red represents highest pressure above normal, due to highest compression.
- Blue represents lowest pressure below normal, due to greatest depletion.

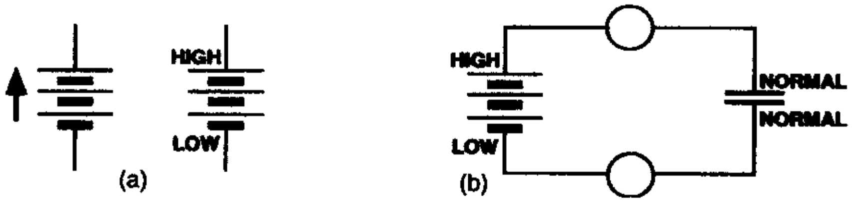

FIGURE 3 3a: Revised battery model; 3b: Unified circuit model.

These five colors are sufficient for most purposes, and Susan used them in the discussion with the tutor to illustrate her thoughts about pressure change in wires and capacitor plates caused by a pressure difference in the battery terminals.

The evidence that she has now adopted the tutor's idea that a battery is a device that maintains a pressure difference in its terminals is operational: From now on, she routinely begins reasoning about circuits by coloring the battery's (+) terminal red and its (–) terminal blue, and then uses the pressure concept to talk about charge moving from a region of yellow or green pressure to the blue terminal.

Summary of episode 3. In this episode, Susan used the pressure idea to unify her understanding of different kinds of circuit components. This explanation appears to have been constructed in a step-wise manner using (a) an initial *sending out* model of the battery as a springboard for conceptual change, (b) her prior knowledge of the behavior of air under compression as an analogy for the behavior of charge in the top capacitor plate, and (c) an emerging interest in explanatory coherence or completeness.

Rather than being motivated by a discrepant event, Susan appears in this episode to have been driven by the sense that there *ought to be a causal agent* driving charge out of the bottom plate during capacitor charging. She indicates that having to think about movement toward and away from the capacitor "in two different ways in your head" is so unacceptable that "It just blows me away!" In thinking about the type of causal agent, (a) sending-out made sense for movement out of the battery along path A, but not for movement out of the capacitor along path B; and (b) pressure-pushing did make sense for path B, when the battery was reconceptualized as a device that maintains pressure below normal in its bottom terminal (as well as above normal in its top terminal). This new element of her model appears to have originated in a successful mapping from the jelly jar analogy introduced by the tutor.

Surprise #4: Bulb B does not light (if bulb A has more resistance). The fourth surprise was precipitated by a circuit that did not have a capacitor, but that had *two kinds* of bulbs. Susan was told that the top bulb (A) in the circuit of Figure 4 is "difficult" for charge to move through (meaning high resistance), while the bottom bulb (B) is "easy" (low resistance). Susan predicted incorrectly that both bulbs would be lit. This expectation was based on having already observed identical bulbs in series with a battery and nonidentical bulbs in parallel with a battery—situations where there are equal pressure differences across the bulbs. However, she observed that the bottom bulb is *off* at the same time that the top bulb is brightly lit. That this was not at all what she had expected is indicated by a very strong expression of surprise and dissonance:

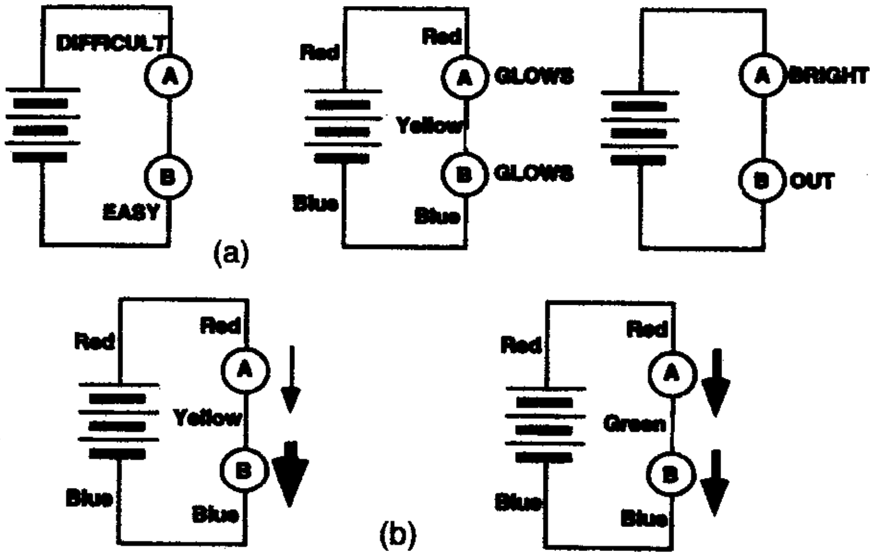

FIGURE 4 Figure 4a: Nonidentical bulbs; 4b: What Susan expected; 4c: What Susan observed; 4d: Initial unstable state; 4e: Final steady state.

4.1. SUSAN "Aah, ooh. Wait a minute. That wasn't supposed to happen! (laughter) That's really strange!"

4.2. SUSAN "Wow! I thought they were both going to light because there was a two step difference between both bulbs, and this would be lighter (i.e., brighter; points to bulb B) because it's easier for that charge to go through."

In the vocabulary introduced earlier by the tutor, "two step difference" means two *color* difference: red-to-orange-to-yellow across one bulb, and (equal value) yellow-to-green-to-blue across the other. The ease with which Susan is using this new vocabulary suggests she is finding color-coding useful for *visualizing pressure values* in the circuit. On logical grounds, the next step would be to reason that unequal flow rates into the middle wire implies that there has been a change of pressure in that wire.

However, this was not immediately apparent to Susan. She understood that the flow rate through bulb B is abnormally low, and she began reasoning about implications for flow in the middle wire. Yet, her path to the logical explanation was slowed by a preconception that there must be *equal rates of inflow and outflow* for any wire. For the middle wire, then,

4.3. SUSAN: "...as much leaves as comes in. So if only a little bit is coming in here (moves finger downward through bulb A), that means only a little bit is coming in here (moves finger downward through bulb B)—and a little bit isn't enough for this bulb (points to B) to light, because it needs more."

4.4. TUTOR: "Can I ask you, what's pushing you to think that as much has to come in as goes out?"

4.5. SUSAN: "I don't know, really. It's just one of those, like, gut feelings."

The feeling did become more tentative, however, and the tutor helped make it more so by reminding Susan that *pressure* is what causes movement:

4.6. SUSAN: "...however much comes in, you're going to have as much leaving. And you wouldn't, like, have more of it leaving than is going to come back in to replenish it? Do all wires have a tendency to want to...[have equal inflows and outflows]?"

The tutor encouraged Susan to start reasoning with the pressure idea—and to see what that implies about flow.

4.7. TUTOR: "No. Now, knowing that that doesn't have to be true, think about this again: Two color pressure difference (points to bulb A), two color pressure difference (points to bulb B)—difficult place (bulb A), easy place (bulb B). And tell me about this [middle] wire: How much is going into it, compared to how much is going out?"

4.8. SUSAN: "Less is coming in (moves finger downward through bulb A) than is going out (moves finger downward through bulb B)."

The tutor now draws a narrow arrow beside bulb A and a wide arrow beside bulb B, as in Figure 4d, to represent small flow rate through bulb A and large flow rate through bulb B.

4.9. SUSAN: "That would really...(pause)... Would that really change the color of that wire then?"

4.10. TUTOR: "Oohh. Tell me about that."

4.11. SUSAN: "Whatever is coming through here (animatedly moves fingers and hand downward through bulb A) would turn into orange. But there is more of it leaving (repeats gesture for bulb B). So it over compensates, and gets rid of what would make it orange—but also takes even more away (repeats hand motion for bulb B again), which would turn it green. So I think that would make it green."

Susan's remarks in line 4.11 appear hastily formed in a rush to exploit an emerging possibility for explanation and may seem confusing. We offer the following interpretive "translation":

> Let's assume the middle wire starts out at yellow (normal) pressure. Charge coming into the middle wire through bulb A will raise the pressure in the wire to orange (above normal), if charge is not also leaving through bulb B. However, charge is also leaving through bulb B, and this will reduce the pressure in the middle wire below the value it would have if that did not occur. Since bulb B is an easier place to get through than bulb A, there will be a larger charge outflow through B that reduces the pressure in the middle wire more than a smaller charge inflow through A will raise it. The net effect will be to reduce the pressure in the middle wire to green (below normal).

This understanding was confirmed in the posttest, where Susan reasoned about the same pair of series bulbs plus another pair with the same bulbs interchanged.

This is a major step forward. Teachers of electricity will recognize in line 4.11 a level of qualitative causal reasoning that is extremely rare among students receiving conventional electricity instruction. The tutor is hoping to find additional evidence of solid understanding, and directs Susan's attention to the effect of the change from yellow pressure to green pressure in the middle wire on flow rates through the bulbs:

> 4.12. TUTOR "Whose got the bigger pressure difference?"
>
> 4.13. SUSAN "The one on top."
>
> 4.14. TUTOR "You have a big push through a difficult place and a small push through an easy place. What is that going to do to the movement? A minute ago there was a big movement through here [bulb B] and a small movement through here [bulb A]."
>
> 4.15. SUSAN "... you're going to have a larger push through here (brackets bulb A with thumb and fore fingers of same hand held over wires on each side of bulb) and a smaller push through there (makes a briefer gesture toward bulb B). Your arrows are going to change."

Imagery. Now that there are no capacitors in the circuit, note that Susan has been talking at length about super-fast transient movements that cannot actually be observed. How is she able to reason about them? We hypothesize that she is imaging them—accessing and conducting mental *simulations* with images derived from transient movements during capacitor charging and discharging, which she had previously observed by means of bulb lighting and compass deflection on an enormously expanded time scale. These images are supported by external drawings and color codings (for pressure values). However, we will argue that the images are not fully comprised by the external drawings, since the drawings do not capture her conceptions of movement inside the wires that is such a prominent feature of these protocols.

We will take Susan's hand motions across the bulbs in lines 4.8 and 4.11 as evidence for mental images of movement. In 4.11 she appears to use her new electric pressure and flow concepts to run a mental simulation of a new situation. This leads her to generate new predictions and inferences that make sense to her. It is less compelling, but still tempting, to regard her motionless bracketing of the bulbs in line 4.15 as originating in an imagined final *steady difference* of pressure in wires connected to the bulb—three color steps (red-to-green) account for the "larger push" through bulb A and one color step (green-to-blue) for the "smaller push" through bulb B. These hypotheses will be developed further in the discussion section.

Susan agreed with a statement by the tutor that the narrow arrow by bulb A will become wider (larger flow rate through bulb A) and the wide arrow by bulb B will become narrower (smaller flow rate through bulb B), because of the increasing pressure difference ("larger push") across bulb A and the decreasing pressure difference ("smaller push") across bulb B. The tutor wanted to find out if Susan understood that the system finally arrives at *steady* pressures differences that drive equal flow rates through the two bulbs.

4.16. TUTOR "Now you're gonna have as much coming in as you have going out [for the middle wire]. Will the green change to something new or not?"
4.17. SUSAN "It would go back to yellow, I think."

The tutor decided to be more directive than usual here. She said to Susan "I'm going to tell you that that answer is not right," and briefly described what is actually happening at the middle wire:

4.18. TUTOR "You've got some coming in and the same amount going out."
4.19. SUSAN "OK. Now it would stay green."
4.20. TUTOR "Do you know why you wanted to say yellow first?"
4.21. SUSAN "I was sort of thinking evening out and going back to the normal."

The tutor returned to this issue at the next session. This was to make sure that "evening out" now means equalization of flow rates as in Figure 4e into and out of the middle wire, rather than equalization of pressure differences across the bulbs:

4.22. TUTOR "So now that the pressure is green, look at these two flows and talk about how much is coming in and how much is leaving."

4.23. SUSAN "...according to the arrows, I would say that it's about the same... which makes sense, because even though the pressure difference is greater up here (points to bulb A) than it is down here (points to bulb B), this (bulb A) was more difficult for the flow to—for the pressure to go through."

Her comments in line 4.23 suggest that Susan has learned to analyze the circuit as a *system*—(a) coordinating the interaction of circuit components, (b) accounting for feedback from downstream as well as feed-forward from upstream, (c) recognizing that the assumed initial state is unstable, (d) reasoning through the subsequent transient process, and (e) recognizing the presence of self-regulation in a final dynamical stable state characterized by equal flow rates into and out of each wire.

Summary of episode 4. In this episode, Susan further improved a model that already associated pressure-based causal agency with individual components of all types. She extended ideas learned in the context of capacitors to other elements of circuits without capacitors. This led to the construction of an integrated description of pressure-driven circuit dynamics: Each component, anywhere in a circuit, influences charge movement at all other points in the circuit.

We have attempted to address the question of how Susan, with the help of her tutor, was able to construct this complex dynamic model, which she used to reason about the consequences of parameter changes in the system. We hypothesized that she was able (a) to *run mental simulations* of movement in circuits with multiple causes and with changes occurring over time, and (b) to use these complex simulations to determine various relationships between variables. We will return to the status of the evidence for imagery and simulation in the discussion section.

Summary of Susan's Model Revisions During the Protocol

Susan exhibited four surprises, each of which preceded a cycle of model revision. The issues dealt with and the revisions adopted are listed in Table 2.

A fifth issue—What happens in bulbs?—was dealt with didactically. Most students initially believe bulbs *use up* what reaches them through the wires, but Susan abandoned the idea after sensing *pass-through* during capacitor charging and discharging. This allowed the tutor to get by with a model generated simply by stating that one bulb type is "difficult" to move through and the other type is "easy"—a primitive, but for now sufficient, conception of electrical resistance.

EVIDENCE FOR REASONING WITH THE NEW CONCEPTIONS

As part of a posttest, Susan was given the following problem to probe her ability to reason with this key concept in a more complex context than she had seen before:

> If a wire is added to the circuit in Figure 5a to form the circuit in Figure 5b there will be
>
> ___left-to-right flow, ___right-to-left flow, ___no flow
>
> through the added wire. Explain your reasoning.

5.1. "On these it will start out as yellow..." (Points to wires connecting the two pairs of bulbs in initial circuit in Figure 5a).

5.2. "Greater movement, greater flow across—through this bulb." (Moves finger downward over easy bulb at lower left). "And this is difficult." (Points to upper left bulb. Colors left middle wire green.)

5.3. "And over here you'd have just the opposite happening." (Points to bulbs at the right.) "Because more is moving into this [right middle] wire than is moving out—because this [lower right] is a difficult bulb." (Colors right middle wire orange.)

TABLE 2
Issues Raised by the Four Surprises That Led to Model Revisions

Issues About Charge Moving in Circuits	*Initial Models*	*Revised Models*
1. Where does it orginate?	Battery only	Also in other conducting parts of a circuit
2. What is making it move?	Battery only	Also pressure from compression in capacitor.
3. How do patteries push?	Sending out	High or low pressure in battery terminals.
4. What happens in wires?	Flow in = out	Unequal in or out flow alters pressure in a wire.

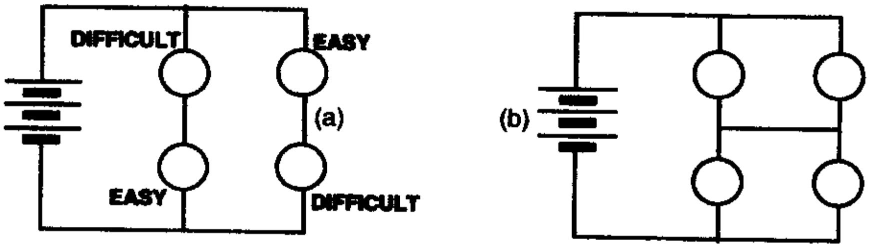

FIGURE 5 5a: Initial circuit; 5b: With added wire.

Here, Susan expertly re-enacts the unobservably rapid transient process that produces "green" pressure in the left middle wire, and the reverse dynamic that produces "orange" pressure in the right middle wire. Her attention now shifts to the final circuit with the added wire, and to its relation to the initial circuit:

> 5.4. "Now!!!" (Long pause.) "I don't think I've quite ever seen anything quite like that."

The complexity of this problem makes it a significant transfer problem for Susan. The lengthy pause and the comment that follows it suggest she is facing a truly novel situation. We believe such responses were provoked by having to deal with new degrees of complexity:

1. None of her previous instructional problems had as many bulbs.
2. None had bulb connections that cannot be characterized as series or parallel (or some combination of these).
3. None had as many wires that do not touch the battery (and thus lack an easy reference or starting point for determining pressure).

After the pause, Susan began reasoning about the dynamic that would be initiated by adding the extra wire:

> 5.5. "Before [adding] that wire, it's gonna look like this over here." (Points to initial circuit.) "And when that wire is added there [in final circuit], I'm thinking about the whole idea of wires that are touching here and touching there [at bottom of initial circuit], and they're both blue—both blue. Just from looking at these wires [in middle of final circuit], without thinking about difficult and easy and all that, I would think about them being the same color."

In line 5.5, Susan appears to wonder about the applicability of the principle that wires connected to each other are always at the same pressure. She learned earlier that the uniformity of pressure comes about through a transient process that is made super-fast by the negligible resistance of wires—and is quite appropriate for the blue (or the red) wires connected to the battery. However, this principle is not appropriate for the orange and green middle wires before the super-fast transient process that will occur after they are connected through the added wire. Here, Susan demonstrates the ability to set aside a tempting principle and go back to something more fundamental—namely, the mechanism that underlies the principle:

> 5.6. "But I think about this [orange wire in initial circuit] being an area of greater concentration than the green area."

5.7. "I'd say that what's essentially happening is you're taking that [extra wire] and you're hooking that wire between them [orange and green areas]. And the charge—the current is gonna—the pressure's gonna move from an area of higher pressure to an area of lower pressure." (Waves both hands from right to left.)

5.8. "And so there will be a charge moving through that wire, and it's gonna move from the right to the left—coming from this area of higher pressure to an area of lower pressure." (Moves finger from right to left over extra wire in final circuit diagram.)

Finally, the tutor asked Susan about her confidence level on a 5-step scale, ranging from *very confident*, the highest step, to *confident*, the next highest step, and so on:

5.9. "I'll say that I'm Confident [vs. Very Confident] only because I don't think I've quite ever seen anything quite like that, with the difficult and easy bulbs and the idea of having it move."

5.10. "It's too new for me to think that right off the bat I'm gonna be right. So I'd say that what I've worked through in my mind seems to make a lot of sense to me, but I've worked things through before and they don't necessarily come out that way."

Summary of posttest episode. Susan has apparently acquired a full set of mechanistic principles needed for analyzing steady-state circuits and the consequences of parameter changes. Electric potential, in the low-abstraction form of electric pressure, is seen as the causal agent of current propulsion. In this episode, Susan demonstrates considerable robustness of her integrated model of pressure-driven system dynamics, by applying it in a new situation of considerably greater complexity. In doing so, she gave additional evidence of using imagistic mental simulation in reasoning with the model. Data taken from classes using a similar approach on a similar transfer problem are provided in the appendix.

Was Susan an Especially Strong Learner?

Does Susan's achievement mean that she was an especially adept learner? To some extent she was made to appear uncommonly adept by the tutor encouraging her to articulate her ideas, providing useful feedback, and assuring her that she was making progress. Mental powers that would have remained more latent in a classroom setting were thereby given greater opportunity for expression.

On the other hand, Susan is the only student we know about who articulated the internal discrepancy in episode #3. Even allowing for a "Pygmalion effect" from the tutor, she appeared to us to be unusual in the intensity of her demand for conceptual coherence. However, we suspect that once raised, most students will have the explanation problem Susan experienced, despite the fact that few may feel exercised enough to articulate it spontaneously.

We have described only the high points of Susan's conceptual change episodes to describe her progress in an article of acceptable length. That has made her appear unusually efficient at managing conceptual change. Susan actually spent much time wrestling with confusion, discussing side issues, and reasoning down blind alleys (e.g., pursuing a model with outflow at both ends of the battery). Her classroom teacher described her aptitude in science as above average, but not exceptional. We therefore caution against seeing Susan as an exceptionally adept learner, although she is probably above average.

DISCUSSION

Summary of Evidence for Conceptual Change

What evidence do we have that Susan has gone through a process of conceptual change? We infer from her early responses that she began with a quite common, but primitive model of the battery sending something out at both ends through two wires that lead toward a bulb. There are two sources of evidence that by the end of the instruction she had developed conceptual understanding of a more sophisticated pressure-driven model of charge flow that is closer to an accepted model: (a) evidence from the later part of the instructional transcript, and (b) evidence from the posttest problem transcript.

Evidence for Conceptual Understanding From the Instructional Transcript

At many points during the later parts of the instruction, we have indications that Susan understands the circuits being presented after working through them because she is able to *give a coherent explanation in her own words* of why there are different pressures and flows at different points in the circuit. In addition, there is evidence from the instructional transcript that Susan's knowledge is *generative* because she actively *pursues gaps in her existing model* by recognizing where an explanation is missing and asks questions of herself (e.g., during Surprise #3). These two observations provide evidence that her understanding was not superficial, and are a first indication that conceptual change has taken place.

Evidence For Conceptual Understanding From the Posttest Transcript

The posttest question given to Susan is a genuine transfer problem in the sense that it involves new features she had not encountered earlier during the instruction, namely the problem involves 4 resistors, and has a path not in a perimeter of the circuit. As a result, it is a fairly stringent test of the depth of her understanding. Her transcript from this problem indicates that she has a robust conception of electric potential, which she can apply to unfamiliar situations of fairly high complexity in the following ways:

1. She is able to reason using pressure differences in wires as the current driving agent in the circuit, in a manner that is fully divorced from batteries. Other studies have found that potential difference is a stubbornly difficult concept that typically remains unlearned after instructional interventions (Cohen et al., 1983; Niedderer & Goldberg, 1996).
2. Furthermore, she is able to deal with dynamical pressure changes based on comparing inflows and outflows to a conducting region. Her initial conception of a wire as a flow-directing pipe did not prevent her learning to think of it in a conceptually different way as a tank in which compression occurs.
3. She gives a coherent explanation in her own words of the pressure changes that will occur as the original system passes through a transient process to a state of steady flow. Thus, she is able to describe and deploy a new system of hidden variables/entities that comprise a mechanism of current propulsion.

In short, there is evidence that a simplified, but complex and powerful model has been constructed. What she has learned can be viewed as a central prerequisite for preparing students to deal with the quantitative concept of electric potential at any point in a circuit, contiguous to a battery or not.

In summary, we have evidence for conceptual change from Susan's think-aloud material in the instructional transcript, and from her posttest transcript. These indicate that she now has a model that is different in structure from her initial model as well as much more complex, and that it is a generative model that she can apply to unfamiliar situations of fairly high complexity to generate predictions and explanations that are in large part correct. Because the form of her reasoning and explanations are very similar late in the instruction and during the posttest, we attribute the overall conceptual change to her instructional experiences.

Intermediate Explanatory Models Utilizing Dynamic Imagery are the Form of Her New Conceptual Understanding

In this section we ask the following questions: What is the nature of Susan's new understanding? What is the form of the new knowledge that she has acquired? We will propose several hypotheses based on this case study: (a) that it resides in explanatory models of mechanism, (b) that the models are at an intermediate level of abstraction or generality, and (c) that these models are dynamically imageable. Hypotheses like the previous two have been difficult to evaluate in the history of our field; here we will cite initial evidence for them that can be evaluated further in future research.

Modest Generality

It can be argued that Susan's final models are of modest, or intermediate, generality in terms of the number of situations to which she can apply them. They are more general than particular observations in that Susan applies her pressure and flow ideas to a large variety of circuits, including ones she has not seen before. Like the diagrams being used, her models are schematic: There are correspondences to features of concrete objects, but other features have been "stripped away" from the representation as inessential. This allows Susan to apply her model, for example, to circuits of different sizes and shapes.

Clearly, however, Susan's model is not yet as general as formal principles in physics such as Kirchoff's Laws. (Her model with color coding for pressure values does include Kirchoff's loop rule for circuit loops implicitly, but has no place yet for loops in empty space.) Thus, it is at an intermediate level of generality (White, 1989).

Dynamic Imagery

We will assume that Susan's spontaneous use of highly depictive hand motions during the instruction (in lines 2.28, 4.3, 4.8, 4.11, and 4.15) and during the posttest (in lines 5.2, 5.7, and 5.8) provide some evidence that the models she is using are not represented only in terms of verbal rules, but also in terms of dynamic mental images. We start from Finke's (1989) definition of *imagery* as "the mental invention or recreation of an experience that in at least some respects resembles the experience of actually perceiving an object" (p. 2). Here we will also extend the previous definition to include the possibility of dynamic images of events and of (kinesthetic) images of forces.

What indicators can tell us when a subject capable of using imagery is likely to be using imagery? That spontaneous depictive hand motions can stem from imagery use has been argued extensively by McNeil (1979). Clement (1994a, 1994b) observed that hand motions were generated by expert problem solvers working on difficult problems, and that they were often accompanied by many other plausible imagery indicators such as spontaneous verbal reports of "imagining" manipulating an object. Monaghan and Clement (1999) also reported the same observations for students. Both McNeil and Clement argued that hand motions can be closely tied to meanings and are often not generated from verbal representations in a second stage of thinking. Finke (1990) has documented evidence for imagery use by students in creative problem solving. Given the findings from previous literature, we will assume here that most students are capable of using imagery during problem solving, and that depictive hand motions are one source of evidence for imagery use. However, no imagery indicator used here is conclusive on its own, so we will use such observations only as initial evidence for hypotheses about imagery use.

Assuming Susan is capable of using imagery, the question remains as to whether there is any evidence that she was using imagery in the particular episodes previously described. Susan's hand motions suggest the hypothesis that she uses dynamic images of fluid-like flows caused by pressure differences. For example, in the following passages from her posttest transfer problem solution, Susan's hand motions over the drawing are highly suggestive of internal dynamic imagery:

> 5.7. "I'd say that what's essentially happening is you're taking that [extra wire] and you're hooking that wire between them [orange and green areas]. And the charge—the current is gonna—the pressure's gonna move from an area of higher pressure (Waves both hands from right to left) to an area of lower pressure."
>
> 5.8. "And so there will be a charge moving through that wire, and it's gonna move from the right to the left—coming from this area of higher pressure to an area of lower pressure" (Moves finger from right to left over extra wire in final circuit diagram).

Because language is our primary tool for communication, it is notoriously difficult to obtain direct evidence for imagistic processes. What seems very hard to refute as a starting point is that her thinking was using circuit drawings as an important tool and that it was quite concrete in the sense that her descriptions refer to pressures and flows or movements within specific parts of the circuit. The evidence here is less diverse than in Clement (1994a, 1994b), but we propose the use of an imagistic representation in these episodes as a likely hypothesis because it provides a coherent explanation for several observations, namely, the hand motions, the generation of drawings, and the level of concreteness in Susan's explanations involving unobservable events. Although some might argue that Susan's only spatial representations are *external* drawings and color codings (for pressure values), we have argued that her imagistic representation is not fully comprised by the external drawings—because the drawings do not embody movements or forces. That is, we take Susan's hand motions along with her statements and drawings in these sections as evidence for the hypothesis that she is imaging those movements and forces internally and dynamically, and that this helps her make inferences such as predicting that charge will move from an area of high pressure to an area of low pressure.

In summary, we hypothesize the use of mental simulations involving dynamic imagery of movement or pushing during Susan's posttest solution. As previously noted, similar hand motions were also observed in the final episodes of her instruction. This provides some additional evidence for the conclusion that the instruction fostered the development of a mental model that can generate new mental simulations involving dynamic imagery for understanding a relatively difficult transfer problem.

Explaining Flexible Transfer via Imageable Models

How would the previous hypothesis allow us to account for Susan's ability to apply her model to a relatively far transfer problem in the posttest? In this section we speculate that it is due to two important properties:

1. *Her models are not formalizations expressed in an abstract notation, but are spatially manipulable, imagistic representations of concrete mechanisms.* The implications of this hypothesis are summarized in the upper right hand corner of Figure 6 (in the first rows of the last two columns). Use of an imageable explanatory model with pressure differences driving currents would have temporal and spatial properties that are not inherent in more formal representations such as equations. In the former representation, electric pressure appears to be an imageable property of a point in a circuit something like the way temperature is a property of a point in a heating system. The inferencing operations Susan applies to these ideas do not appear to be primarily acts of induction or deduction. Rather, they appear to be acts of mental simulation. She appears to "imagine what would happen" to the electric fluid under the influence of certain pressure differences. This has a very different character than logical deductions operating on formal principles or equations. Instead, the models are expressed as rather concrete images of objects. We hypothesize that this allows her to efficiently apply everyday spatial reasoning processes to the model and its instantiations and this allows her to rotate and assemble model elements flexibly in many spatial configurations, not just ones in the same configuration as the examples she learned from. This provides the outline of an explanation for aspects of the ability to flexibly apply the model to transfer problems. It may also allow the model to be accessed perceptually (Larkin & Simon, 1987).
2. *Such models are concrete, but general.* We think of these models as being concrete in the sense of being imageable representations of objects, but at the same time as being somewhat general in the sense of being *schematic* objects stripped of detail, in a way that can be applied to a large number of cases. We hypothesize that this allows Susan to apply the model to transfer problems that may differ in many ways from the problems she learned from. This leads to a view that may on the surface seem somewhat paradoxical: Explanatory models can be quite general and still

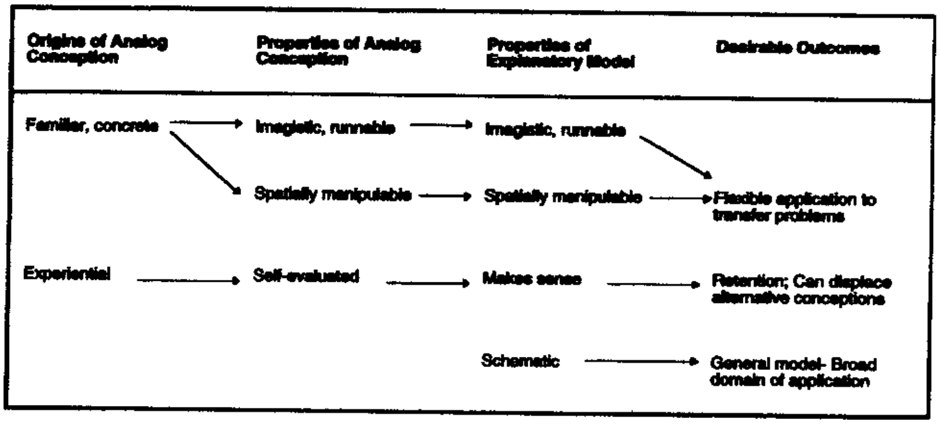

FIGURE 6 Hypotheses for how analog conceptions can be used to build powerful models.

be concrete—general in the sense of applying to many cases and concrete in the sense of being imageable in a way that accesses accompanying spatial reasoning operations used in object and event perception. This effect is summarized in the fourth row under the headings of Figure 6.

This makes plausible the advantage of an explanatory model using internal schematic imagery for flexible transfer. In summary, we have proposed that Susan's new knowledge is comprised of *concretely imageable explanatory models at an intermediate level of generality*. We view this as an extremely important level of knowledge, which allows her to perform flexibly and competently on an unfamiliar transfer problem. Because it is so inherently difficult to obtain evidence for specific uses of imagery, our claim that imagistic simulations are contributing to flexible transfer here must remain a theory that awaits further confirmation. Yet, we are intrigued with its ability to provide a coherent framework for explaining Susan's way of talking about movements of imagined charges, and her use of similar drawings, color coding, and hand motions to describe events during instruction and in an unfamiliar transfer problem.

Learning Processes Involved in Conceptual Change and Implied Instructional Strategies

So far we have focused on the final form of Susan's knowledge structures in this discussion section. In what follows we will discuss major findings and propose general processes that we believe played a role in Susan's learning. We will discuss each topic from two perspectives: (a) A summary of findings that are grounded in observations from the protocols, and (b) more general hypotheses comprising elements of a theory of learning and instruction that can explain the results. These hypotheses, which have only their initial grounding in this case study, may suggest additional research that can evaluate them further.

An Evolutionary Sequence of Models and Modifications

Findings. The sophistication of Susan's explanations grew steadily during the instructional treatment. In each of the four transcript sections presented in this article, it is apparent that Susan was able to build on knowledge that she had developed in earlier sections. This suggests a view that has *model evolution* as its central feature. The transcript suggests viewing Susan's normative conceptual changes here as producing a sequence of progressively more expert-like models of electric circuits. These move from a sending-out model of currents moving out from both battery terminals, to a circuital fluid flow model with sending-out at only one battery terminal, to a model involving pressure in a compressible fluid, to the inclusion of below-normal pressures and a battery that maintains above- and below-normal pressures in its terminals, and finally to a model involving multiple transient flow rates. The experiments appear to trigger surprises in Susan that initiate processes of change from one intermediate model to the next. At several stages analogies are suggested by the tutor to feed ideas into this process. The revisions after each surprise are summarized in Table 2.

Instructional theory. Figure 7 shows the hypothesized form of this model generation, evaluation, and modification or GEM cycle as it affects conceptions in the mind of the student (Steinberg & Clement, 1997). The figure shows only a few of the cycles, but as many cycles as are needed can be added. (Many more of them are required in the full CASTLE curriculum.) The three rows in the figure, from top to bottom, represent the student's Prior Knowledge, Evolving Explanatory Model, and Observations. The middle row shows the development of the student's model with time going from left to right and begins with the student's own initial model labeled Model 1, used to form an explanation and prediction for the first example of a circuit presented before instruction. The prediction will usually conflict with the student's Observation 1, shown in the bottom row. The resulting dissonance is symbolized by the zig-zag line between Model 1 and Observation 1. This dissonance motivates the construction of Model 2, (usually a modification of Model 1; sometimes a replacement for it).

The construction of Model 2 may be facilitated by the introduction of an analogous case (often from the teacher, but sometimes from the students) that is useful as a starting point for constructing the model. Useful schemas that are activated by the presented analogous cases are shown in the top row labeled Prior Knowledge.

For example, Susan appeared to have a prior conception of air stored under pressure in a tire and this was used as a starting point for the idea of charge stored in a capacitor plate. The modification to Model 2 is successful if it is constructed so that it explains Observation 1 more adequately than Model 1 did. The cycle can then be repeated as many times as needed. (Students will also use other elements of prior knowledge about bulbs, wires, batteries, and air that are not included in the analog conceptions, but these are not depicted.)

Figure 8 uses this same notation to represent a basic theory of intermediate models and learning processes involved in the sections of Susan's protocol presented here. Although the diagrams in Figures 7 and 8 can be used to indicate the order in which teaching "moves" were implemented, they go beyond this in representing a theory of the cognitive events taking place in Susan in response to, and sometimes in spite of, the tutor. (Again, these diagrams omit a number of "blind alleys" in the full transcripts and are therefore simplified and idealized.) A diagram showing the cyclical form of the model generation, evaluation, and modification cycle appears in Figure 9. If model evaluation detects a minor problem, the model is modified in an attempt to remedy the problem; detection of a major problem can lead to starting the generation process over again. Interestingly, this is essentially identical to a cycle documented in expert modelers (Clement, 1989).

Our challenge in the next sections will be to discuss how individual strategies such as analogies and discrepant events were able to produce conceptual changes in Susan's model.

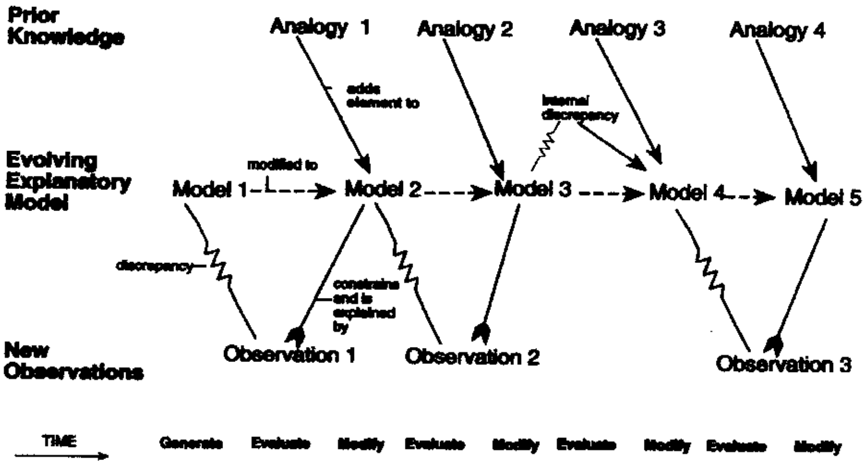

FIGURE 7 Role of analogies and observations in GEM cycle of model generation, evaluation, and modification.

Discrepant Events and Experiments That Foster Modeling

Findings. The first sources of surprise and evaluation in the instructional sequence were the discrepant event experiments used to motivate model revisions. We have seen that these did in fact produce reactions of surprise and were eventually followed by model revisions, and that Susan was then able to explain the events satisfactorily. Susan exhibits reactions of surprise (Surprises 1, 2, & 4) from three discrepant events. She appeared to become engaged in trying to explain the discrepant events rather than downplaying or ignoring them. Some of her reactions were quite strong, revealing a motivating effect, as when only one of the bulbs in a series circuit lights up in line 4.1: "Aah, ooh. Wait a minute. That wasn't supposed to happen!" This is followed by an energetic discussion with the tutor about how to explain the event. Thus, discrepant events appeared to play a role in motivating the student to search for an explanation.

Instructional theory. We take the reactions of surprise from discrepant events to be evidence for internal dissonance with an existing conception. These are shown as jagged lines in Figures 7 and 8. Each surprise indicates dissatisfac-

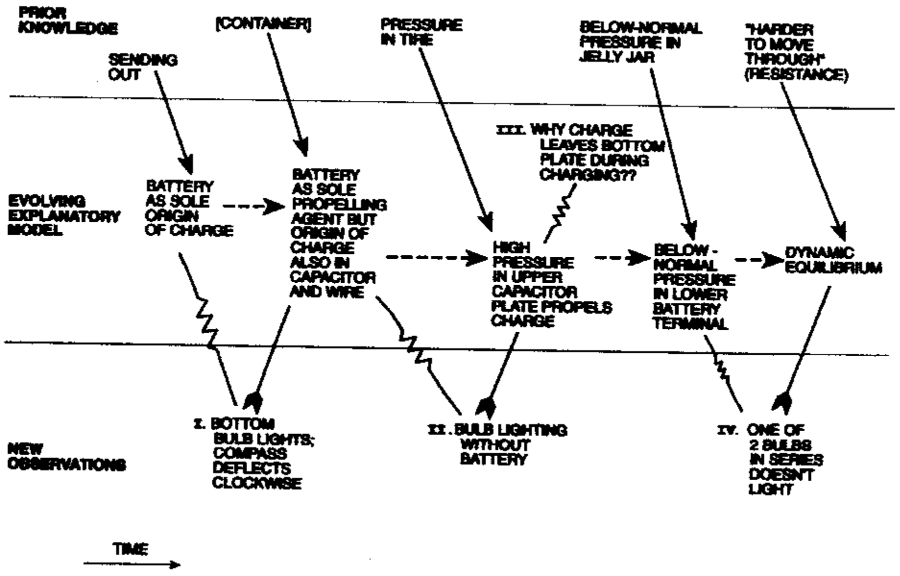

FIGURE 8 Sequence of four surprises and model revisions in Susan's session.

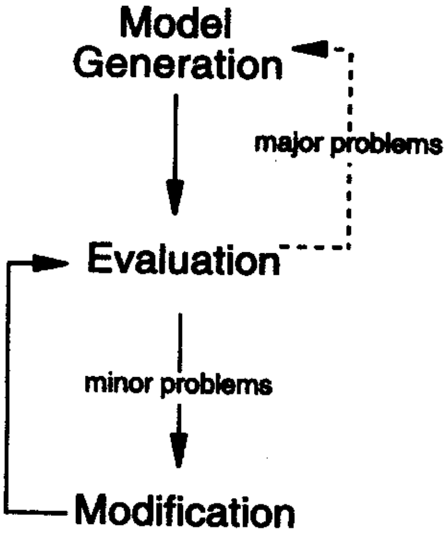

FIGURE 9 GEM cycle of model generation, evaluation, and modification.

tion on the part of the student with her current model and constitutes an implicit evaluation of it. (Authors such as Chinn & Brewer, 1993, pointed out that other reactions are also possible: e.g., the student may reject the observation or ignore it.) The experiments were carefully chosen to point out a specific, isolatable deficiency in this model.

Another hypothesis is that these same experiments played a positive role in making hidden mechanisms easier to visualize and model. The series of events was designed to encourage the expansion of the student's model in small, doable steps. In particular, we hypothesize that the use of circuits containing capacitors was successful for several reasons having to do with the temporary (transient) movement of charge into and out of the capacitor plates:

1. Transient bulb lighting in circuits with capacitors exposes "battery centered misconceptions" (such as the idea that batteries are the only sources of charge) by exhibiting lighting in broken circuits and in circuits without batteries.
2. Capacitors slow down normally superfast transient processes in circuits, while underwire compasses provide visible evidence for charge movement. Also, in the initial experiments charge moves into and out of the capacitor plates rather than in a continuous circuit, thus fitting the simpler idea of "transfer" rather than the not-always-true idea of "continuous flow." These features make the movements and their causes simpler to identify and model imagistically.

3. This makes possible model revisions that are small enough to make immediate sense. The resulting model progression leads to a concretized conception of electric potential that supports qualitative causal reasoning about circuits.

Resolving Internal Sources of Dissatisfaction

Findings. The instance of Surprise #3, caused by Susan's internal recognition of a missing cause in her model, provides evidence that discrepant events are not the only sources of dissatisfaction for motivating conceptual change. After identifying the cause of movement out of one capacitor plate during discharging, she became impatient with her ignorance of what causes movement out of the other plate during charging. Because no new circuit experiment was performed, we took this as evidence for an internal source of dissatisfaction.

Instructional theory. We hypothesize that Susan used an intuitive sense of internal consistency and symmetry here to criticize her models. diSessa (1983) and Hammer (1994) have noted that many students do not embrace the two aesthetics of consistency and symmetry as strongly as scientists, and therefore may need to be enculturated into the scientific community's way of evaluating theories. However, Surprise #3 illustrates that even for novices, dissatisfaction may not always come from an empirical observation. It indicates that Susan was capable of a second form of evaluation, in which the motivation for revision comes from an internal dissatisfaction. In this case it takes the form of a missing cause, but in other situations it might take the form of a recognized inconsistency between the new model and an older, trusted model.

Air Pressure Analogy as a Starting Point for Model Building

Findings. A pressure analogy was used as a starting point for constructing Susan's model of current propulsion. The teacher introduced the familiar imagined case of air in a punctured tire to introduce the concepts of compression, pressure, and pressure difference. Susan was able to apply the analogy during the instructional session and make mappings from it onto the circuit to explain the reason for charge flow without a battery in the circuit. Susan's continued use of the pressure concept during the posttest interview indicates the continuing effect of this analog conception on her thinking. Her descriptions of the complex causes of flow in the circuit appear to be based very much on the pressure concept introduced during the instruction.

Instructional theory. A prior knowledge schema for the situation of air pressure in a tire is shown in the top row of Figure 8 and was used as a starting point for the concept of "electric pressure." Notice that analog schemas (shown in the top row) are differentiated from the evolving explanatory model (shown in the middle row). The analog schema serves as a source of elements for constructing or modifying the developing model. As pictured in Figure 10, we hypothesize that important aspects of the analog conception that generates dynamic imagery and that was available to Susan for thinking about pressure and fluid flow in the tire is now built into her model for thinking about electric potential and current. We refer to this transfer of schema elements that generate imagery as "transfer of runnability" from the analogy conception to the model. (In the larger CASTLE curriculum, students who lack sufficient prior knowledge of pressure and current in fluid flow problems are first given additional hands-on experiences with "air capacitors" and syringes to strengthen these concepts.)

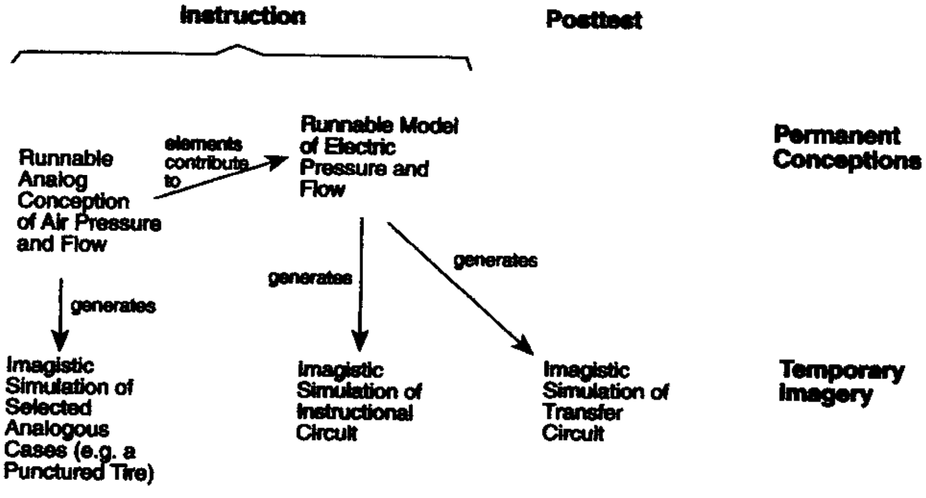

FIGURE 10 Transfer of runnability from an analog conception to an explanatory model and ultimately to a transfer problem.

Multiple Analogies and the Role of Imagistic Simulation

Findings. At several stages in the sequence, additional analogous cases were used as sources for adding elements to the model. Thus, this unit involved the use of *multiple* analogies (see also Glynn, Doster, Nichols, & Hawkins, 1991; Spiro et al., 1989). For example, an evacuated jelly jar was used to introduce the concept of below-normal pressure. There is evidence that for the most part Susan was able to incorporate fairly immediately such newly suggested features, as they appear immediately in her explanations.

Instructional theory. The evacuated jar is shown as Analogy 3 in Figure 8—a prior knowledge element that contributes to the growing model M. Notice that the jelly jar itself is not incorporated into the model. Rather, elements of the analog conception involving below-normal pressure that are marshaled intuitively by Susan in understanding the jelly jar are incorporated into a revised model of the battery as a device that creates below-normal pressure in one terminal (and above-normal pressure in the other terminal).

Thus, one attempts to draw certain features selectively from each analogy to add a component to the evolving model. This is one reason researchers, teachers, and students need to distinguish the model from any particular analogy. In this case the student's original "sending-out" model of a battery has been modified into a pressure-creating (and pressure deficit-creating) model. The "sending-out" model has probably not been utterly abandoned, but Susan has at least learned not to use it in this context.

Based on these episodes, we can now speculate on a theory for why analog conceptions can add power to an explanatory model, as shown in Figure 6. Starting from the upper left and moving right, if the analog conception has its origins in familiar, concrete experiences, it is likely to be a runnable conception that can generate dynamic imagery of the event. The real payoff comes when these dynamic properties are transferred to the explanatory model under construction. We view this transfer of runnability as one of the central functions that analogies can play in instruction. This in turn means that the model is spatially manipulable, allowing it to be applied in more diverse situations. Collins and Gentner (1987) hypothesized the process of model growth from the contributions of multiple analog conceptions, but here we develop this idea further in terms of models that generate dynamic mental imagery.

Moving to the third row of Figure 6, an analog conception might be familiar and concrete, but still be based on "hearsay." A conception that is based in personal experience is also likely to be intuitive in the sense of being self-evaluated rather than evaluated by a peer or by an authority. Other studies have used the term *anchoring conception* for a self-evaluated preconception that is in rough agreement with currently accepted theory (Clement et al., 1989). The tire analogy appears to be an anchoring case here because Susan understands the case intuitively in a self evaluated manner. Grounding a model in such a conception could give the subject a feeling of the model "making sense" and could increase the retention of the model and perhaps enable it to compete with persistent alternative conceptions when those are present. Thus, Figure 6 outlines a theory of how analogies contribute to science learning via imagistic simulation in the deep sense of learning general and flexible scientific models.

Use of Student Drawings

Findings. Susan was asked to make drawings of most of the circuits she encountered and a color scheme was introduced to represent levels of electric potential. Arrows of different sizes were used to represent current levels. Once she learned these notations, she generated and referred to drawings extensively when asked to give explanations.

Instructional theory. These representational tools appeared to be very important for Susan's learning. We hypothesize that they did this by,

- Providing a way to represent externally model elements that are invisible in the actual circuits (e.g., potential and current).
- Allowing her to express and record model modifications in a transparent and memorable way.
- Supporting Susan's use of internal imagery. As argued earlier, we believe that they could not have replaced the use of mental imagery for Susan since the drawings do not embody movements or forces. Yet, they provide a perceptual framework within that such internal dynamic imagery can occur more easily, along with a way to record its results.
- Being a shared reference point to facilitate precise conversations with the tutor.
- Focusing Susan on particular properties such as the idea that potential is the same everywhere within a wire (via use of color coding).

Model Evolution Versus Simpler Approaches

Susan's case highlights the evolutionary approach that may be necessary for building complex models. In this view, models of systems as complex as electric circuits cannot be constructed in a single intervention. The model evolves over a period of time through a longer chain of conceptual changes. We can contrast this to other approaches:

- *Versus the use of one discrepant event.* The approach involved a *series* of surprising experiments rather than relying on one discrepant event.
- *Versus the use of experiments alone.* The three levels shown in Figure 7 reflect the view that contributions were made both "from above" as well "from below" as observations interacted with prior conceptions. Thus, the process fits an interactionist view of learning as empirically constrained, creative model construction rather than an empiricist view of learning as generalizing from observations.
- *Versus the use of a single analogy.* The approach used a *series* of analogies for adding pieces to the model over an extended period of model construction, rather than relying on one quick analogy. This highlights the distinction between individual analogies and the larger model under development. This is not to say that single analogies are never useful (they were used on occasion; e.g., in Camp et al., 1994). Rather it reflects our view that a single analogy would be insufficient for developing a model of this complexity.

How the Teaching Strategies Worked Together to Support Learning via Abduction

Overview

We have hypothesized that Susan learned to think with models that could generate images of pressure and flow to analyze novel transfer circuits. Most of these models were not presented directly to Susan by the tutor. How then could such models capable of generating imagistic simulations be learned? How did they originate? For example, the idea of electric pressure building up in wires is a new idea for Susan. What is the nature of the model generation process that constructs it? In this section we examine how the processes of model generation and revision might be better understood theoretically. Although we do not have as much detailed information from the protocol at this level, we use the data we do have to motivate theory here as a way to add coherence to our previous findings and to explain how multiple teaching strategies may work together systemically to support learning. This section also serves to illustrate the active nature of Susan's contributions to model construction even when the tutor is guiding the learning by asking key questions.

We will first give an overview of our hypothesis, then examine its support. Peirce (1958) and Hanson (1958) used the term *abduction* to describe the process of formulating a hypothesis which, if it were true, would provide an explanation for the phenomenon in question. In their view, the hypothesis could even be a guess about a hidden mechanism at work in the system as long as it explained the observations collected so far. In this section we will argue that the core of Susan's model generation process is neither inductive nor deductive, but is a more conjectural abductive design process. We also hypothesize that cycles of evaluation and revision help to make up for the tentative nature of each conjecture and to make the overall process a powerful one.

Uses of the Term Abduction

Magnani (1999) describes two epistemological meanings for the term *abduction*:

> A Narrower Sense: the formation of explanatory hypotheses (We will call this "generative abduction" when it refers only to the act of hypothesis generation or revision);
>
> and
>
> A Broader Sense: Inference to the best explanation, including hypothesis generation, evaluation, and revision cycles and comparisons between rival hypotheses. (Here we will use the term *model evolution* for this larger set of processes.)

We will focus first on the narrower process of generative abduction within a single cycle of model generation (or revision). We will assume that for purposes of this discussion that there are enough similarities between model generation and model revision that we can treat them together as both utilizing generative abduction. Thus, generative abduction is thought of as being a complementary and different process from hypothesis evaluation at some level. As conceived by Peirce (1958) and Hanson (1958), the possibilities are rather open for how generative abduction might occur, and it need not take place via traditional logical inferences such as deduction or induction by enumeration. In some cases it might simply be a guess, where the subject pieces together a conjectured model that explains the phenomenon. Details about how abduction may actually occur in humans are poorly understood, and providing some initial case study data for developing models of abduction is part of the purpose of this section.

Some Candidate Instances of Generative Abduction From the Transcript

Abductive model construction processes, evaluation, and revision cycles can be sustained by a single individual (e.g., as documented in Clement, 1989). In Susan's case the situation is more complicated because of the careful guidance of the tutor. However, because Susan articulates several of the model revisions before the tutor does, we believe that she is doing some generative abductions, although the context for these is certainly set up by the tutor (e.g., lines 1.9–1.12, 2.16, 4.8–4.11). So in Susan's case we refer to "teacher-supported" or "scaffolded" abductions. There are several candidate instances of generative abduction from the transcript where Susan

- 1.9–1.12: Explains the direction of flow in the bottom bulb in Figure 1 by proposing that charge must be coming out of the bottom of the capacitor, despite competing ideas to the contrary.
- 2.16–2.17: Builds on the tire analogy to propose that capacitors are never empty of charge.
- After Surprise #4: Proposes that the middle wire in a series circuit with only one of its two bulbs lit may be at same potential as the lower wire to the battery.
- 4.8–4.11: Proposes that unequal amounts of charge may be entering and leaving a wire temporarily.

Protocol Example of Generative Abduction

We will consider the last two instances mentioned previously in more detail as illustrating scaffolded cycles of generative abductions and evaluations.

Incorrect abduction. After Surprise #4 (see transcript presented in earlier section, lines 4.1 and 4.2) Susan proposed that the middle wire in the series circuit with only one of its two bulbs lit (Figure 4c) may be at the same potential (blue) as the lower wire going to the battery:

> "If this bulb [B] doesn't light does it mean: it's blue on the other end [middle wire] too; for the pressures to be the same?"

Given that the bottom bulb does not seem to be "operating," this is a reasonable (although incorrect) conjecture. However, Susan proceeds to criticize and reject her abduction:

> "It doesn't make sense. Making this [middle wire] blue would be like saying that the bottom bulb is controlling the whole thing—whereas this top bulb has to influence it somehow too."

Susan's spontaneous criticism leads to rejection of the previous abduction. This episode illustrates the idea that an abduction leading to a false hypothesis can be rejected by evaluation processes. It also indicates that Susan is capable of generating a cycle of model generation, criticism, and rejection.

Second abduction. In line 4.3 the tutor has just had Susan focus on the pressure conditions shown in Figure 4d, and asks about transient flows into and out of the middle wire. Susan abduces an inflow-equal-to-outflow model :

> "...as much leaves [the middle wire] as comes in."

Evaluation. She then matches this model with the phenomenon in the following simulation of its implications in line 4.3:

> So if only a little bit is coming in here (moves finger downward through bulb A), that means only a little bit is coming in here (moves finger downward through bulb B)—and a little bit isn't enough for this bulb (points to B) to light, because it needs more.

Although the question is about the initial transient condition, and she has not answered that correctly, this abduction is in fact very close to the scientist's model of current and resistance for the later steady state condition, and so she might very well have stopped there. However, she continues to search for ways to deepen her understanding of the anomaly:

> Susan: This bulb (points to bulb B) is dependent on this bulb (points to bulb A), it would seem.
>
> Tutor: Dependent for?...
>
> Susan: ...Well, I was gonna say it's dependent because there is as much potential charge ready to leave (points to bottom of middle wire) or empty out into this low pressure area (moves finger downward through bottom bulb to bottom wire) as comes in from this high pressure area (points to top wire). But then I have to stop because it's [pressure in the top wire is] not pushing from behind [not pushing the charge moving through the bottom bulb from immediately above]. It's [charge moving through the bottom bulb is] not coming from there (points to top wire). It has to do with here (points to middle wire).

Here Susan seems to be examining even more possibilities. She returns to the idea that one bulb has control over the situation, but this time it is the top rather than the bottom bulb controlling the amount of current that flows through both bulbs. As she does this she returns to pressure ideas. However, she then criticizes this new control model as well, by realizing that she should be reasoning from local pressure differences rather than pressures acting a ways downstream in the circuit to control things "at a distance." This is a key step toward understanding the role of pressure in circuit wires, and it exposes some of the alternative conceptions that should be explored if students are to have resilient understandings.

Thus, Susan was not satisfied with her earlier explanation in line 4.3 that did not use pressure ideas. She appeared to want to understand the situation more deeply by trying to connecting it to ideas of "control" and pressure. She appeared to be seeking a deeper and more coherent explanation of the anomaly via a cycle of repeated generative abductions and criticisms. Abduction here seems to take the form of an exploration of possibilities or factors that could play an important role in the situation.

To encourage Susan to make a causal agent connection, the tutor then reminds Susan that *pressure* difference is what causes movement and asks why Susan thinks as much has to go in to the middle wire as comes out. In 4.5 Susan states the following:

> Susan: "I don't know, really. It's just one of those, like, gut feelings."

Revised abduction. Susan begins looking elsewhere for a useful idea in thinking about the initial instant of flow:

> "...you wouldn't, like, have more of it leaving [the middle wire] than is going to come back in to replenish it?"

Elaborated revision. This last line appears to be a breakthrough, in that it is the beginning of developing an adequate model that can explain the cause of intermediate potential levels in series circuits and that can handle the two bulb anomaly. Then in line 4.8 we hypothesize that Susan reasons by simulation in response to a question from the tutor as follows, with accompanying depictive hand motions: That same pressure difference across low resistance bulb B as across high resistance bulb A will temporarily make more charge leave the joining wire through bulb B than is coming into it through bulb A (see Figure 4d). This reinforces her newly revised abduction of unequal inflow and outflow by integrating it with model elements she has already learned.

Explanation of the anomalous event. Susan then spontaneously infers from a further simulation in 4.11 that pressure in the middle wire will fall, resulting in less pressure difference across bulb B (which explains why it is out) and more pressure difference across bulb A (which explains why it is lit). Because these events explain the anomalous behavior of the circuit, her new model receives some positive support. Later she is able to analyze an even more complex circuit on her own using this same kind of reasoning about transient flows (lines 5.1–5.8).

If we take the hand motions in these episodes as suggestive of the use of imagistic simulations, we can hypothesize that the revised abduction in line 4.6 is confirmed, extended, and elaborated by running simulations from the growing number of model element schemas at her command and noting the results, culminating in her being able to explain the anomaly. In summary, in the previous passages one can see the student making and evaluating generative abductions that alternately move both away from and toward the scientist's model.

Construction Occurs via Abduction Rather Than Induction or Deduction

It would be convenient if students had a reliable algorithm for inferring model elements automatically from the data in front of them. However, we hypothesize that Susan's process of generating model elements was considerably less automatic and more inventive and tentative in the form of an abduction or educated guess.

Generative abduction is not the same as deduction. In a deduction, results are derived via logical rules that combine statements assumed to be true to produce a new statement that should be true. We did not observe Susan making such formal inferences in the instances of generative abduction previously listed. Her explanatory models appear to consist of constructions that can explain events in the circuit, not formal deductions from prior principles. Furthermore, the hypotheses in question were all initially quite tentative when she posed them, and certainly did not carry the confident sense of validity one hopes for from a deduction.

Nor is abduction the same as induction. By induction here (formally, induction by enumeration) we mean a process by which a more general principle is abstracted from a set of empirical observations. The principle then serves as a more abstract summary of a pattern in the observations. In Susan's case the model developed appeared not to be distilled via induction from a set of observations; rather, a theoretical model was constructed at a different level by adding nonobservable elements to it from prior knowledge in a form of generative abduction. There are several arguments for this conclusion. First, the elements of the model are at an entirely different level from the phenomenon. Pressure, charge, and flow are never directly observed in the circuits—these are inventions created at a theoretical level to explain observations at an empirical level. Thus, an explanatory model is not just a pattern in or summary of observations—it is a hidden mechanism not initially subject to direct observation. Here model revision appeared to occur abductively as an educated guess for the next component of the model being designed to explain the phenomenon, rather than a summary of a pattern in a set of observations (induction). Second, in each of the episodes mentioned previously, Susan was participating in the development of an explanation primarily for a *single* example of a circuit, not for multiple examples. Thus, the character of the process appears to be very different than induction from multiple instances.

As used here, a defining constraint on abduction is the need to produce an explanation of the phenomenon. Presumably though, a scientific abduction would aim to satisfy various other constraints and desiderata for scientific theories; the most basic of these are that the model be plausible as a mechanism that could actually be operating in the system, that it not use occult powers, that it be coherent with previously developed elements of the theory, and that there be some attempt at precision in describing it (as opposed to being satisfied with a loose literary metaphor). This leads us to hypothesize, along with Thagard and Shelley (1997) and Darden (1991), that the process is one of design under constraints. That is, it is a "create the most plausible explanatory model that occurs to you" strategy—essentially a guess—but a very educated guess when informed by multiple constraints. Here some of these constraints were provided by the existing model elements already developed, such as the idea of charge traveling through pipe-like wires and being stored in tank-like capacitors; and some were provided by experimental observations.

Analogy can Contribute to Generative Abduction

Thagard and Shelley (1997) and Darden (1991) have proposed that there may be a close relation between analogy and abduction, and Clement(1989) provided evidence from an expert case study that this could be true, but what exactly is the nature of the relation? Based on the case study, we hypothesize that an analogy can make a contribution to a generative abduction by suggesting the form of a model element as a building block. We have argued that the models Susan constructed were capable of generating imagistic simulations. In the theory presented here, generative abduction includes the process of forming a new image of a mechanism that could be operating in the circuit [target] and the role of an analogy is to help shape that image. For example, when the analogy is air being forced through a small hole in a tire, neither the tire nor the hole nor the air become part of the model. However, the analogy serves as a guide to constructing an image of some air-like, compressible entity called charge that flows through the wires and other circuit components. This image shares some features with the source analog, but not others. Therefore we consider analogy-inspired formations of new model elements to be constructions that still require an additional process beyond analogy and we call the overall process generative abduction. In this sense, "generative abduction" simply means "constructing an explanation," but with an emphasis on the idea that it can be an act of creative design and that it need not be an act of either deduction or induction by enumeration.

Yet, should we think of a model growing out of an analogy provided by the tutor as a student's abduction? Because the student rather than the tutor constructed the mapped counterparts in the model in working from the source analogs here, and because elements of the model are different than those of the analogy, we consider such analogy-inspired formations of new model elements to be part of a process of scaffolded abduction on the part of the student.

Abduction Within Modelling Cycles

Small cycles may support learning complex structures. In general, the challenge posed by each surprise appeared to be a hurdle for Susan; she had to work on gradually increasing her ability to use new ideas consistently in her explanations and needed to apply the new ideas to new examples to make progress. (The brevity of the sections of transcript included in this article for space reasons belies the significant amount of time taken for Susan to fully accommodate to each surprise; these intervals varied from 10 to 90 min of work.) This suggests that avoiding the intermediate models she developed by taking on more than one challenge issue at a time could have caused an overload situation and have been counterproductive. We take this to mean that instruction should be designed in small, "mind-sized" steps when constructing complex models, as illustrated in Figure 11. Here the small step sizes of the revisions were made possible by the careful choice on the part of the tutor of coordinated "small" analogies and "small" discrepant events.

We have inferred that many of these evaluations and revisions operated on imagistic simulations of pressures and flows in circuit elements. The level of effort put forth by Susan suggests that this imagery is complex and unfamiliar, and that she would be unable to construct the complete, complex simulations of the target model all at once. The imagery system in humans is limited by the amount of detail that it can represent readily and by the speed with which new imagery can be learned. This is a more specific reason that explains the need for small step sizes. Yet, we hypothesized that the potential payoffs for learning via runnable models are great—in particular, the enhanced ability for flexible transfer. Thus, the theory of small abductive learning cycles developed here provides us with an initial explanation of how a student can learn flexible ideas via image-generating models, even when they are complex.

Systemic source of the benefits of an evolution by abduction strategy: Evaluation cycles compensate for conjectural abductions. Abduction is a more conjectural form of inference than logical deduction or induction over many

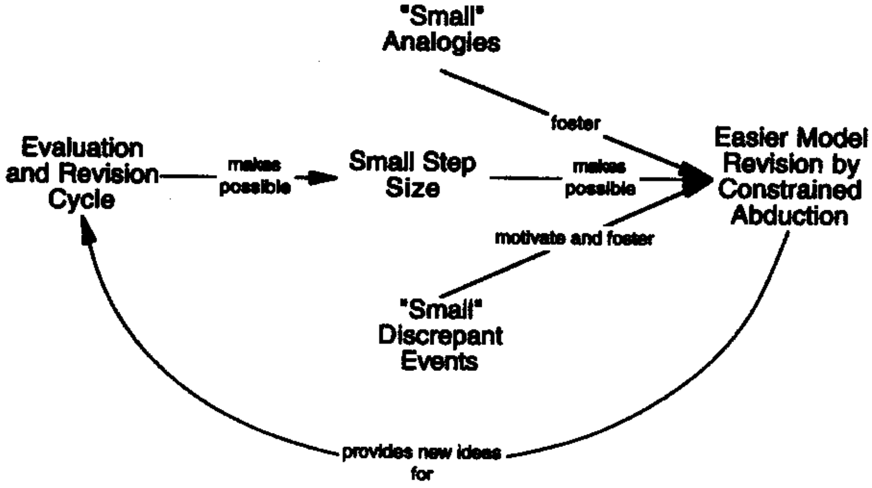

FIGURE 11 Coordinated instructional strategies for complex model learning.

instances and appears to be more open ended; how then could it be a powerful learning process? This can be answered by hypothesizing that generative abductions can be more powerful when used in conjunction with an evaluation and revision (evolution) process. In this view individual generative abductions are not decisive and may be rejected or revised, but the overall strategy is strong because repeated evaluations and revisions can "home in" on a good model despite elements of trial and error in each abduction and the possibility for missteps.

In this view a strong evaluation process is an important complement to generative abduction. And there is an advantage to informed revisions: the idea that the revisions can utilize the previous criticisms as new constraints to guide the direction of the revision. This makes them "intelligent" revisions that contrast with a pure "series of random guesses" process such as that used in a simple model of biological evolution. Thus, we hypothesize that repeated evaluation and revisions cycles can make up for the possible missteps in any particular abduction. This gives added meaning to relations between the various teaching strategies shown in Figure 7, where analogies supporting abductions are coordinated with discrepant events that evaluate them, promote revisions, and provide new constraints for abduction.

Here the role of the tutor was also very important in guiding Susan to participate in model evaluations and revisions by providing discrepant experiments and questions, and also guiding her to make connections with her existing knowledge. Each of Susan's intermediate models had various coherence relations with other beliefs at the time when a dissonance relation was introduced via a discrepant event. This is a faithful reflection of the fact that model evaluation in real science is a complex affair. Attempts to formulate formal models of this and some other aspects of abduction and coherence have been described by the philosophers Harmon (1989), Thagard (1978), Thagard and Shelley (1997), and Darden (1991) has hypothesized some of the abductive strategies used by scientists in the history of genetics.

Section Conclusion

If most of Susan's model elements were not received directly from the tutor, how did she generate them? In this section we have made a start on unpacking the processes of model generation and revision. In reviewing several of these instances in this section we have hypothesized that the generation process was abductive rather than deductive or inductive. The process of generative abduction is poorly understood, but we do have some evidence here that

- Susan was able to generate and evaluate abductions when the context was set up by the tutor.
- Analogies can contribute to generative abduction.
- Abduction can form models that generate imagistic simulations.
- Conjectural abduction processes can be successful when backed up by a larger evaluation and revision process.

Additional research is required to explicate these processes further. We have speculated that in addition to analogy, the remaining core of the generative abduction process is something like an act of design under constraints leading to an "educated guess." As such, it is often considered more conjectural than deduction, or induction over a sample; but we have portrayed it as being complemented by a cycle of evaluation and revision that makes up for this to form a powerful learning process. Thus, in this section we have proposed a theory for how three processes can be mutually supporting as a system for fostering learning: abductive model generation and revision, model evaluation, and repeated cycles of these last two processes in small manageable step sizes. These small step sizes were fostered by the pedagogical strategies of using "small" analogies and "small" discrepant events.

Perhaps abduction plus evaluation and revision cycles provide a somewhat more detailed explanation for one case of what Piaget and others were attempting to describe in their constructivist emphasis on the need for student "knowledge construction" or "active learning." The process is active in several ways: the acts of model generation and revision by abduction, and the act of criticizing the model. In addition, the subject actively mapped suggested analogies during instruction and generated new imagery in an unfamiliar circuit during the flexible application of the model in the transfer problem on the post test. The active nature of these processes, even when the context is set up carefully by a tutor, contrasts sharply with a learning model involving passive reception.

CONCLUSIONS

Critique

Tutoring versus classrooms. To apply these ideas in the classroom, the cognitive strategies discussed in this article must be adapted and integrated with social and motivational strategies for learning in classrooms. We agree with Driver et al. (1994) and Cobb and Heinrich (1995) that science learning involves both individual and social processes. To achieve this, however, ways must be found to encourage active learning on the part of each student. In classrooms that have adopted the curriculum described in this article, students are encouraged to construct explanations and arguments by working on experiments with each other in small groups organized by the teacher (Steinberg et al., 2000). Between experiments, the teacher guides large-group Socratic discussions where meanings of terms are negotiated and alternative models are compared. This article has concentrated on the problem of obtaining more detailed descriptions of cognitive learning processes, but social learning processes that are central in these interactions are also a very important topic for research. The advantage of tutoring interviews is that much more data on learning processes is obtainable in a systematic way from each student as they "learn aloud." We believe that by describing learning processes in tutoring, we can gain important cognitive models for thinking about goals and methods in the classroom, although those models and methods will need to be modified and supplemented for the classroom.

Process versus content goals. Although the tutor was interested in some process goals, such as the student experiencing the acts of constructing, evaluating, and modifying a model, the content (subject matter) goals had a very high priority in this study. In particular, the tutor was interested in the student attaining a deeper level of conceptual understanding of the material than is commonly achieved. Other models of instruction that apply when process goals have higher priority should also be investigated (White & Frederiksen, 1995). For example, there is no reason to believe that Susan learned much in this session about *designing* experiments so that she could carry on an inquiry cycle of her own. However, we are not sure whether high level process goals and deep conceptual change goals can be optimally fostered in the same lesson in such a complex topic area. Working on such process goals may initially require a less complex domain.

What Susan Learned

In this article we have described an approach to science teaching via a model evolution process. We have documented a case in which a complex model is learned that appears to lead to a deep level of conceptual understanding—knowledge that was deep enough to generate explanations of transfer problems more complex than those used in the instruction. We hypothesized that the knowledge at the core of this conceptual understanding had several characteristics:

1. Susan developed an *explanatory model* representing hidden, nonobservable mechanisms used to explain observable properties of circuits.
2. Based on initial evidence from hand motions, these models were capable of generating *imagistic simulations.*
3. The subject's spontaneous use of similar depictive hand motions during the instruction and during the posttest provides some initial evidence that the instruction directly *fostered the development of these dynamic mental models.*
4. As shown on the right hand side of Figures 6 and 10, to explain how the models could apply to new transfer problems, we hypothesized that they were at an *intermediate level of generality*, able to be applied to a range of situations, but that they were still somewhat concrete in the sense of involving *schematic imagery*, so that spatial transformations could be used to enhance their flexible application to circuits in different orientations and configurations.

Teaching and Learning Processes

Some of the key teaching strategies used were as follows:

- Asking the student to *explain* events, including *discrepant events* producing reactions of surprise.
- *Manageable step sizes* producing a modest and manageable conceptual change.
- Specific *analogies* designed to suggest the form of elements being added to an expanding model.
- *Drawing to learn* supported by notations such as color coding for electric potential.

These strategies were also central to the curriculum used in classrooms that produced higher scores on the posttest problem described in the appendix.

Some of the key learning processes identified in the protocol were as follows:

- *Internal dissatisfaction* produced by discrepant events to motivate and constrain model revision.

- *Internal detection of a missing cause* also producing dissatisfaction with the current model.
- *Imagistic simulation* as the subject "ran" her new models to apply and evaluate them.
- *Transfer of runnability from multiple analogies to the explanatory model.*
- *Model construction cycles* of model generation, evaluation, and modification.
- *Scaffolded abductive knowledge construction* rather than induction or deduction: A process where a new model element is designed within constraints to explain observations.
- Generative abduction and a repeated cycle of evaluation and revision , hypothesized to be *complementary processes* for a powerful learning system, as shown in Figure 11.

More research is required to evaluate the relative import of each individual factor mentioned previously. Our case study initiates this research by showing how each played a role in Susan's learning. In the following paragraph, our theory of the way many of the above factors fit and work together lends plausibility to their importance.

Integrated learning strategies. We can now connect Figures 6, 7, and 11. The theory that the subject is using a schematic and spatially manipulable explanatory model to generate imagistic simulations provides a way for us to explain the student's ability to flexibly apply her knowledge to a transfer problem (Figure 6). The challenges of using imagistic simulation also helps explain the need for small step sizes and the success of using analogies. The overall argument (shown in Figure 11) is as follows: The need for flexible recognition and transfer makes it advantageous for models to be expressed as imagistic simulations. Yet, the human systems for developing and performing these simulations are limited with respect to the complexity of new and unfamiliar imagery that can be added at any one time. This makes it strategic to use small revision cycles so that the model is built up in stages. To do that, the use of multiple "small" or "narrowly targeted" discrepant events and multiple "small" analogies is very useful. A "small" discrepant event serves to criticize one aspect of the existing model rather than the whole model. Coordinating a "small" and targeted analogy with this has the advantage that it can suggest one or more already visualized "seed elements" that can be used to revise that particular aspect of the model. In Steinberg and Clement (2001) we discussed the possibility that the use of small discrepant events and revisions can avoid the problem of reduction of motivation for certain students that some authors have expressed concern about in looking at the use of dissonance in instruction (Dreyfus & Eliovitch, 1990; Smith, diSessa, & Roschelle, 1993; Stavy, 1991).

The theoretical hypotheses described previously have their initial grounding in data from the present protocol, but further research is required to evaluate them. This kind of hypothesis generation is one of the appropriate functions of an exploratory case study. The positive learning results seen in Susan and the classes described in the Appendix from using this strategy leads us to believe that the short abductive cycle strategy supported by small analogies and discrepant events has the potential to foster complex learning and that it merits further testing.

General Educational Implications

The subject's final model was hypothesized to be one that could generate explanations via imagistic simulations of fluid-like flows caused by pressure differences and use them in relatively difficult and unfamiliar problems. This fits the general goal of enabling students to develop a conception of causal models in science that allow them to generate satisfying explanations and solve transfer problems—in short, to be able to think and reason flexibly with what they have learned. We are beginning to compile a better understanding of the possible teaching techniques used to foster this goal. The topic of electric circuits at this level requires a relatively complex model, but this is not true of all science topics. Further research in other topic areas may allow us to develop guidelines for when to use each technique depending on the characteristics of the topic being taught.

We need to become better able to articulate the ways in which abductive modeling cycles are different from induction or deduction, because it is our impression that very few teachers understand these differences and there are immediate implications for instruction. It is already commonplace in science education to say that instruction needs to take place at other levels in addition to the formal level of mathematical formulas and the deductive relations between them—that it needs to avoid working exclusively at too high a level of abstraction. However, it is not as common to warn that instruction must also avoid working exclusively at too low a level of abstraction. This focus on abduction is consistent with the idea that sufficient learning does not automatically happen (e.g., by induction from common observed elements) when the students are simply exposed to many concrete examples; the role of abducted models at an intermediate level of abstractions of hidden elements explaining the examples appears to be central. Because these are skeletal in form, they can generate schematic images that are general (applicable to many instances) while at the same time being concrete (imageable representations of objects).

If confirmed, the elements of the theory of leaning and instruction developed here and summarized in Figures 6, 7, and 11 would suggest the following educational implications. The key to generating flexible scientific models is to get the student involved in reasoning actively about the topic in the particular mode of constructing a visualizable model and running it. The initial model does not need to be correct if students are willing to evaluate and revise the model. Because an imagistically runnable model is built by putting together smaller imagistically runnable schemas, instruction is not effective unless one can put the student into the mode of building and revising simulations. Unfortunately, many students may not be accustomed to learning in this way and need ways to get started (Kolodner, 1997). Because language is limited in its ability to unambiguously describe complex spatial structures and dynamic movements, it is helpful to access by analogy any runnable prior knowledge schemas the student has that can be used as starting point. These serve to get the imagistic reasoning processes started, which is worth a great deal, even though the resulting models may have to be evaluated and improved through several cycles of revision. In this view understanding a system involves an activity or kind of doing: adapting and running an imagistic simulation. Learning by putting elemental simulations together, trying out, running, and evaluating the resulting model, and improving it is a kind of learning by doing. The more traditional view of learning as passive reception contrasts sharply with the need for students to generate and improve on internal imagistic simulations.

This view of instruction is focused on activating the student's natural ability to use imageable mental models, model based reasoning, and grounding for new meanings in prior experiences accessed by analogy. This would imply courses that respect and take account of the students' incoming prior knowledge and reasoning capabilities—courses that draw on, scaffold, and extend the students' natural capacity to comprehend analogies and construct runnable mental models via abduction and evaluation cycles. That is, courses where learning science is seen as an extension of one's natural impulse to understand and make sense of the world, rather than as an isolated academic exercise.

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APPENDIX

Comparing the Teaching Approach to a Control Curriculum

This appendix deals with two issues:

- Is Susan's learning sequence applicable to a real world high-school setting?
- Is it important that the electric potential issue be dealt with using a qualitative, imageable model as a base?

We will present some evidence from data collected in three high schools and two 4-year colleges. With regard to the issue of the importance of the electric potential concept, we found an interesting control possibility in another modern electricity text (Chabay & Sherwood, 1995) that aims to overcome the weakness of conventional physics texts that substitute formalism for mechanism. This text is widely regarded as an outstanding resource for teaching introductory electricity. We are interested in it here because of the opportunity it offers to obtain evidence about the usefulness of a qualitative imageable conception of electric potential.

The control text introduces the electric potential concept in a formal mathematical manner—by defining its values in terms of a path integral over a vector function. If a qualitative imageable conception of electric potential is important for reasoning about circuits, then classes using the CASTLE curriculum should be at an advantage compared to classes using the control curriculum.

Although the control text deals with electrostatics before circuits and CASTLE uses the reverse order, similar instructional goals and the use of similar instructional equipment make these two curricula seem otherwise quite similar compared to all the others:

- Both use capacitors and a compass to investigate circuits.
- Both emphasize qualitative reasoning based on models of mechanism.
- With the exception of electric potential, both develop concepts through hands-on activities that give students an intuitive sense of role in the mechanism of current propulsion and provide visual representation on circuit diagrams.

Therefore, we sense a potentially useful control comparison. Here we provide a preliminary exploration of this issue, based on data from classes in three high schools that used an early version of the CASTLE curriculum (Group A), and classes in two 4-year colleges that used an early version of the control curriculum (Group B). Students in all of the classes were asked to solve a problem shown in Figure 12 that closely resembles Susan's posttest problem.

> Closing the switch S in the circuit of Figure 12 will result in
> ___left-to-right flow, ___right-to-left flow, ___no flow
> through the ammeter A. Explain your reasoning.

We have observed evidence for two major ways students reason about this problem to conclude there will be right-to-left conventional charge flow (or left-to-right electron flow) through the ammeter after the switch is closed:

1. Current takes "the easy path" or "the path of least resistance" after the switch is closed.
2. The pairs of unequal series resistors make electric potential higher in the right middle wire than in the left middle wire prior to closing the switch so that there will be right-to-left flow after the switch is closed.

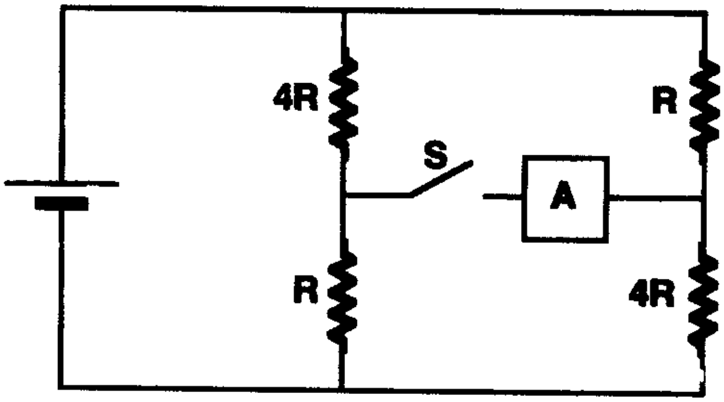

FIGURE 12 Modified posttest circuit.

Using 2 is evidence that the role of electric potential in the current driving mechanism has been understood.

Table 3 shows the percentage of students in each group using each mode of reasoning.

From the data for CASTLE, we conclude the following:

- Class instruction can produce Susan's level of achievement for many high school students, but her level of success is unlikely to occur for more than half the class.

Some reasonable conclusions from comparing groups A and B are as follows:

- The high school group produced significantly more solutions than the college group.
- The high school students learned to reason with electric potential at the level used in this problem in much greater numbers than the college students.

TABLE 3
Percentage of Students Using Different Reasoning Models

Mode of Reasoning	*CASTLE*[a] *Percent*	*Control*[b] *Percent*
1. Path of least resistance.	25	28
2. High → low potential.	34	1*
Total	59	29*

[a]$N = 160$. [b]$N = 80$.
*$p < .001$.

We find the following hypothesis to be highly plausible for explaining the different levels of achievement of the two student groups on this posttest. The experimental curriculum gave the high school students access to a general and flexible schema for qualitative imagistic reasoning in circuits that can be applied to many different circuit geometries. Consequently, they were not confounded by the strange and unfamiliar circuit in this transfer problem and were able to reason about it successfully. Attention to an imageable representation of an explanatory model may be crucial for grasping the electric potential concept, which is generally regarded as being much more difficult than the current and resistance concepts.

Making electric potential imageable by conceptualizing it as "pressure" introduces an *intermediate* concept, which is not used by physicists because it cannot address problems in electrostatic distant action. Is this misleading to students? We acknowledge the *incompleteness*—but would argue that this characterizes every scientific model that is capable of being transformed into a more inclusive model. Pragmatically, the CASTLE curriculum stimulates further revision of the model Susan reached at the end of episode 4. Subsequent investigations lead students from the compressible fluid model with one kind of charge and electric potential as "pressure" only in conducting matter to a distant action model with two kinds of charge and electric potential in all matter as well as in empty space.

It is useful to note that the beginning stages of conventional electricity instruction are also incomplete. They exclude important features of electric circuits, for example,

- Ignoring the mass of electrons keeps plasma waves off the agenda.
- Ignoring the effects of acceleration keeps radiation off the agenda.

These examples are reminders that ignoring features to reduce model complexity, and then adding the features later on, is a universal strategy in science education. Susan's lessons made this strategy explicit by providing resources for revising imageable concepts in a context of ongoing model evaluation and revision.