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Article Title: **Constructive Model Evolution in the Study of Electric Circuits**

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Constructive Model Evolution in the Study of Electric Circuits

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Completion date: 8-28-97

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In this paper we describe an approach to teaching electric circuits that takes a model construction cycle of generation, criticism, and modification as an organizing framework for thinking about when to use each of the above strategies. The approach uses all of the above methods as the students are led to criticize and revise their model many times in the course of the lessons. It is assumed that students need to pass through a series of more and more complex and refined intermediate models in order to make sense of the model targeted by instruction, rather than counting on a single "correct" model to carry all of the weight.

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INTRODUCTION

In this article we analyse tutoring interviews with a high school student who had no prior physics instruction, whom we shall call Susan. The interviews were videotaped for ten hours over a period of five days. The tapes show hands-on investigation of bulb lighting in circuits with batteries and capacitors, accompanied by Susan's think-aloud discussion. The tutor decided which circuits were to be investigated, but otherwise intervened as little as possible.

The interviews revealed early on that Susan held preconceptions which are typical for beginning students:

- What's moving in a circuit comes only from the battery.
- The battery is the only agent that can make it move.

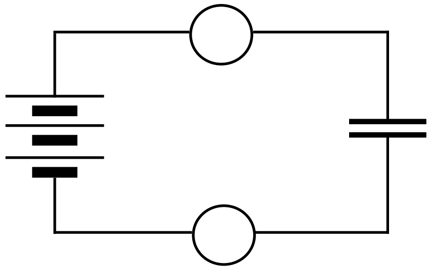
These ideas about current propulsion are normously different from those used by physicists. They will require a great deal of conceptual change to reach the desired outcome of Susan's instruction, which is a robust model of the current driving mechanism in circuits.

The tutoring framework breaks the total desired conceptual change into shorter, less daunting, cycles of model generation, criticism and revision. Within each cycle, multiple conceptual change techniques are exploited to generate and resolve dissonance: [1, 2]

- Each cycle is initiated by a surprise bulb lighting event that reveals a deficiency in Susan's existing model.
- Model revision is facilitated by the analogy that charge in a capacitor plate behaves like air in an automobile tire.

Applying the analogy leads Susan to identify "pressure" in a compressible fluid of mobile charge as the agent of current propulsion in circuits. This idea is the source of growing conceptual coherence in her evolving model.

FIRST AND SECOND CYCLES

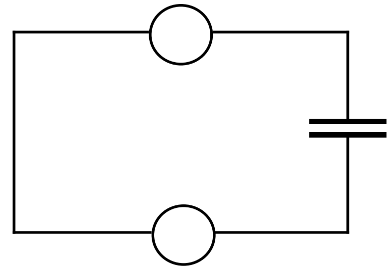


CAPACITOR CHARGING

Surprise #1
The bottom bulb lights!

Criticism #1
Need some way for charge to get below the capacitor.

Charge also originates in metal in the bottom plate.



CAPACITOR DISCHARGING

Surprise #2
Bulbs light with no battery!

Criticism #2
Need a causal agent to push charge out of the top plate.

Pressure from compression is agent pushing charge out.

The first surprise introduced dissonance in the form of an explicit incompatibility between an observation and the preconception that mobile charge originates only in batteries. This dissonance stimulated Susan to abandon her preconception and adopt the view that the charge moving in a circuit originates in all conducting parts of the circuit. No intervention by the tutor was needed.

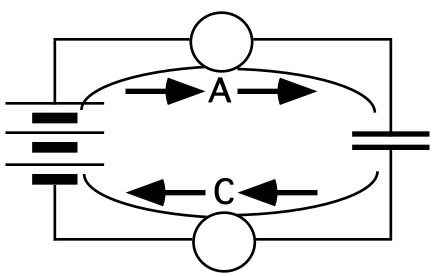
The second surprise introduced dissonance in the form of a sensed discrepancy between an observation and the preconception that only the battery can make charge move in a circuit. This dissonance stimulated Susan to discern the presence of"pressure" in the top capacitor plate, due to mobile charge becoming more crowded there during capacitor charging.

The conceptual change process leading to this novel application of the "pressure" idea was initiated by the tutor asking Susan to change the subject for a while and talk about what happens when a nail punctures an inflated car tire. While discussion of that topic was in progress, Susan began spontaneously describing charge leaving the top capacitor plate during discharging as behaving like air leaving the car tire through the puncture hole:

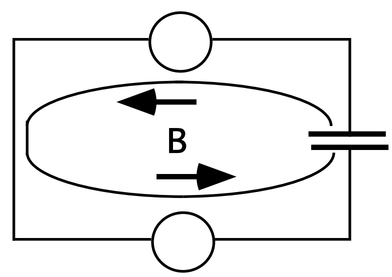
"I was just thinking about the high pressure moving [out of the top plate]. Once it's got that room to move, that place to expand [into the bottom plate], the high pressure is gonna want to move to the low pressure."

Susan was soon describing "that air, that charge, whatever" moving from high pressure to low pressure. The generic language suggests she was using imagery associated with springiness of a compressible fluid. This is a moderate abstraction which can subsume air in a car tire and charge in a capacitor plate, and is well suited to mental simulation. The "pressure" that Susan discerned in electric circuits is a highly intuitive prototype conception of electric potential in conducting matter. The idea was first proposed by Alessandro Volta in 1778. [3] Volta's work made it immensely popular through the middle of the nineteenth century.

THIRD CYCLE



CAPACITOR CHARGING



CAPACITOR DISCHARGING

Surprise #3

No apparent reason to move from bottom plate to the battery along path C!

Criticism #3

"I was just thinking about the high pressure moving ... that the pressure is gonna take that path ..." Path B

"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 C

"This makes complete sense to me..." Paths A and B

"But what is gonna make this charge leave here [bottom capacitor plate] and go to the battery?" Path C

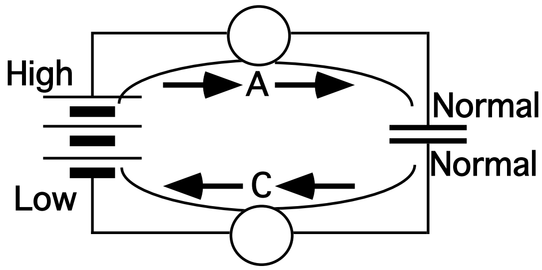
The third surprise introduced disssonance in the form of a sensed incompleteness of explanatory power within the framework of Susan's evolving model. She now has "pressure" as the cause of outflow from a capacitor plate along path B, but cannot apply the idea to explain outflow from the other plate along path C. Her naive squirting-out model of the battery remains the cause of outflow along path A, but she feels great dissatisfaction in contrasting it with the <u>un</u>explained flow along path C. Consider the vehemence: "It just blows me away!"

We suggest that Susan's productive new application of the pressure idea has given her a sense of new possibilities for conceptual coherence. If that is true, then why was she so frustrated? Why didn't she go ahead and use "pressure" to explain flow along path C?

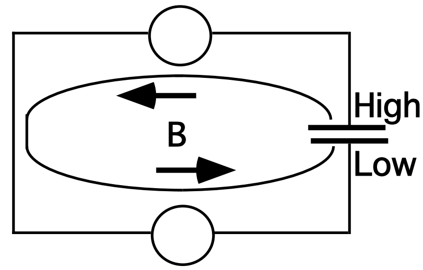
Our experience suggests that Susan was unable to visualize pushing by <u>normal</u> pressure (a common problem for students). Assuming this to be the case, the tutor asked Susan to imagine a jelly jar with the air pumped out and talk about what happens when a hole is punched in the lid. Susan understood that outside air will push into the jar, and soon described this as normal pressure outside the jar pushing toward <u>below</u>-normal pressure inside the jar.

This enlargement of the pressure idea can explain flow along path C if there is <u>below</u>-normal pressure in the bottom battery terminal -- which will provide a place for the normal pressure in the bottom capacitor plate to push into. But how could the battery create below-normal pressure in its bottom terminal? By moving some charge out -- presumably into the top terminal, where it will create <u>above</u>-normal pressure.

The diagram below shows how such a pressure-based model of the battery can provide a coherent explanation of charge flow along all paths for capacitor charging and discharging. But did the third-cycle dissonance and the jelly jar episode stimulate Susan to actually adopt this model?



CAPACITOR CHARGING



CAPACITOR DISCHARGING

Revision #3

We do not have quotes in which Susan articulates her belief in the pressure-based model of the battery described above. But we know that her squirting-out model of the battery was modified to a model in which the battery is a device that creates above-normal pressure in one terminal and below-normal pressure in the other terminal. A great deal of evidence is provided by her consistent productive application of the pressure-based model in subsequent problem solving.

Outflow at the battery's (+) terminal is a downstream effect that differs little from the squirting-out model's prediction. But flow at the (-) terminal is an added feature of the pressure based model that enables it to explain more of what is observed. Note that inflow occurs because low pressure in the (-) terminal has an effect on mobile charge located upstream from the (-) terminal. A student's confidence in the reality of this upstream effect may have the desirable consequence of undermining sequential reasoning -- the widely held belief that upstream can affect downstream, but not conversely. [4]

FOURTH CYCLE

Susan's new pressure-based model of the battery has brought a high degree of conceptual coherence to the way she thinks about overall circuit behavior. Complete coherence will be achieved if she can also construct a pressure-based model of wires. However, Susan's transcript will soon show that she harbors a preconceived model of a wire as requiring equal inflow and outflow rates at all times. This ideal-conduit model rules out compression in wires. It must be modified before Susan can grasp the role of wires in distributing pressure differences to resistors.

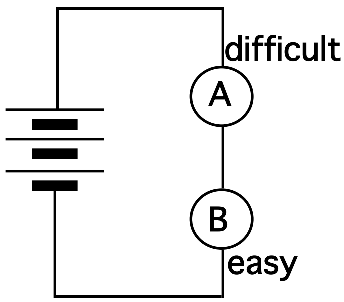
Determining the pressure in wires connected to the battery was easy for Susan, who regarded them as extensions of the battery terminals. But determining the pressure in wires that are not connected to the battery is a task of a very different order. To deal with these cases, there are two relationships that Susan must learn to take into account and coordinate:

- Upstream and downstream resistors control inflow and outflow.

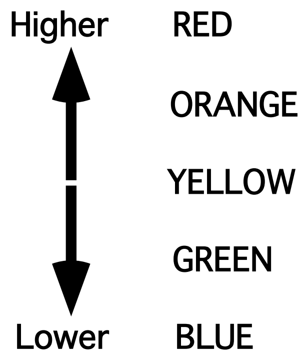
- Compression or depletion occur if inflow does not equal outflow.

Surprise #4

The top bulb A lights brightly, but the bottom bulb B does <u>not</u> light at all!



BULB LIGHTING PARADOX



PRESSURE COLOR CODE

As a quick way to introduce the resistance idea, the tutor told Susan that the top bulb A is "difficult" for charge to get through and the bottom bulb B is "easy" to get through. The tutor also introduced a color code for pressure values which is indicated in the diagram above. Yellow is the "normal" pressure that is present before a battery makes anything happen, while red is the highest pressure above normal and blue is the lowest pressure below normal.

Susan was asked to color code the left circuit above before actually observing the circuit. She colored the top battery terminal and attached wire red, and colored the bottom battery terminal and attached wire blue. She colored the middle wire yellow, because she had previously observed identical bulbs in series with a battery and non-identical bulbs in parallel with a battery -- two situations with equal pressure differences across all bulbs. Her reaction to seeing bulb A lit but bulb B out was:

> "Aah, ooh ---- wait a minute. That wasn't supposed to happen!!!"
> "I thought they were both going to light, because [of] a two-step [color] difference between both bulbs. And this (points to bulb B) would be lighter because it's easier for that charge to go through."

Criticism #4

The fourth surprise introduced dissonance in the form of an explicit incompatibility between an observation and the overgeneralization from instruction that all bulbs are subjected to the same pressure difference. Susan's attempt to challenge this overgeneralization produced further dissonance in the form of a sensed discrepancy between her realization that the pressure in the middle wire must change and a preconception that the rates of inflow and outflow for a wire have to be equal.

Susan understood that bulb B being out implies an abnormally low flow rate through it. Logically, this would lead to the conclusion that the pressure in the middle wire has dropped to a value lower than yellow. But Susan's reasoning about the mechanism that causes this pressure change was hampered by her preconception about the necessity of equal rates of inflow and outflow for the middle wire:

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

When the tutor asked why the inflow and outflow rates have to be equal, Susan replied:

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

Revision #4

To loosen the preconception's hold on Susan's thinking, the tutor noted that movement is caused by <u>pressure difference</u>. The tutor asked Susan to talk about the amount going into the wire through the "difficult" bulb A, compared to amount coming out through the "easy" bulb B:

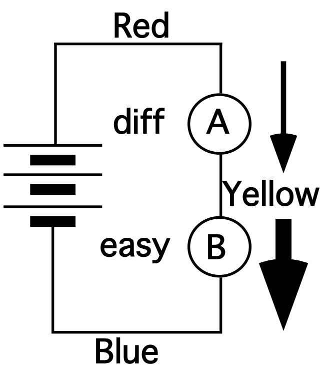
> "Less is coming in (moves finger downward through bulb A) than is going out (moves finger downward through bulb B)."

The tutor drew a narrow arrow by bulb A and a wide one by bulb B, to show small flow rate through A and large flow rate through B. Susan asked: "

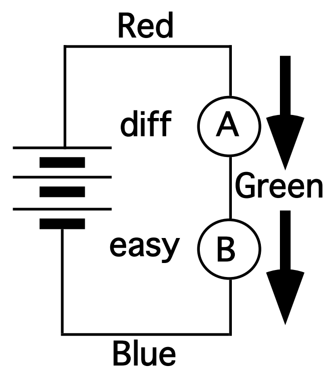
> Would that really change the color of that wire then?"

When the tutor asked Susan to talk more about that, her response was:

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



INITIAL UNSTABLE STATE



FINAL STEADY STATE

To probe Susan's understanding of how a shift from yellow to green pressure in the middle wire will affect flow rates through the bulbs, the tutor asked which bulb has a bigger pressure difference. Her reply was:

> "The one on top."

And what effect would that have on the flow rates through the bulbs?

> "You're going to have a larger push through here (brackets bulb A with thumb and forefinger) and a smaller push through there (gestures toward bulb B). Your arrows are going to change." (to new widths shown in the diagram above right)

Susan is talking here about a transient processes that is much too fast to observe. How is she able to reason about it? In some of the early experiments, she observed capacitor charging and discharging on a greatly expanded time scale. We hypothesize that she is using images formed then to simulate similar processes on a highly compressed time scale.

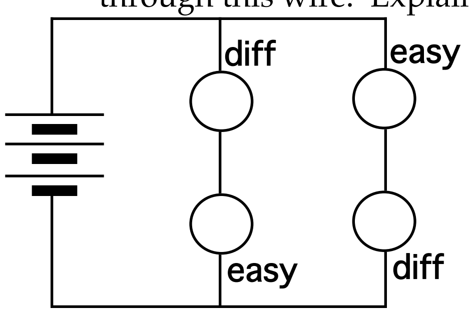
The images are supported by external drawings, with color codings for pressure values. However, the images are not fully comprised by the drawings, since the drawings do not embody movements or pressures. We hypothesize that Susan is imaging movements and pressures, and that this helps her make inferences such as predicting that charge will move from an area of high pressure to an area of low pressure.

Throughout Susan's discussion there appear phrases like "the high pressure will move toward the lower pressure." This raises a potentially troubling question: Is she confusing pressure in compressed charge as the cause of movement with charge as the property of matter that moves? We think not, because there are passages where these concepts are perfectly well sorted out and because there are no instances where lapsing into less careleful terminology led Susan to draw erroneous conclusions.

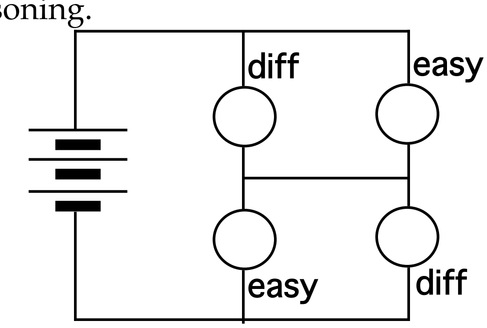
TRANSFER PROBLEM

Susan now has all the qualitative tools needed for circuit analysis. But does she understand deeply enough to solve problems more complex than any she has seen so far? A post-test posed the following problem:

> An extra wire is added to the initial circuit. There will be
> ___left-to-right flow, ___right-to-left flow, ___no flow
> through this wire. Explain your reasoning.



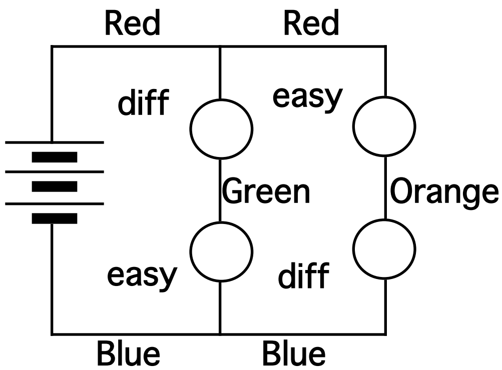
INITIAL CIRCUIT



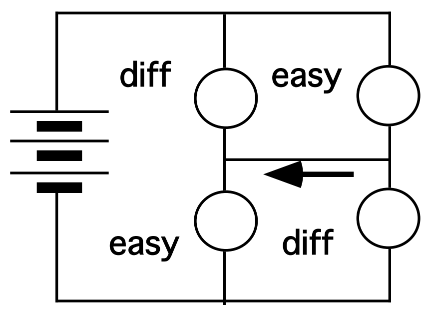
WITH ADDED WIRE

Susan first colored all top wires red and all bottom wires blue in the initial circuit. Then she recognized the left-hand pair of bulbs as a repeat from Surprise #4. But she did not remember the outcome, so she repeated the analysis that assigns green pressure to the wire between the left-hand pair of bulbs. She recognized the right-hand pair of bulbs as an inverted left-hand pair, so the pressure in its middle wire must be orange. Finally, she turned her attention to the circuit with the added wire:

"I don't think I've quite ever seen anything quite like that."
"...I'm thinking about the whole idea of wires that are touching here and touching there -- and they're both blue, both blue..." [bottom of circuit] "Just from looking at these [middle] wires without thinking about difficult and easy and all that, I would think about them being the same color."



COLOR CODED CIRCUIT



FLOW IN ADDED WIRE

Susan is thinking here about the rule that wires touching each other are always at the same pressure. This rule is valid for the red top wires and the blue bottom wires (where the pressure equalized a long time ago). But she resists the temptation to overgeneralize for the orange and green middle wires. She appears to understand that the pressure in these wires will equalize by means of transient flow through the added wire <u>after</u> that wire is connected.

"But I think about this [orange wire] being an area of greater concentration than the green area."
"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)
"And so there will be a charge moving through that wire -- and it's gonna move from the right to the left."
(moves finger from right to left over the added wire)

In this episode Susan applied her model of current propulsion in a situation of considerably greater complexity than any she had encountered before. Her ability to solve the problem without any tutor intervention demonstrates that her model is indeed robust.

We suggest that Susan's copious hand motions are further evidence of using mental simulations of pushing and movement. The hand motions appear to function as kinesthetic depictions of mental images which help in the solution of problems. They support the conclusion that Susan has built a dynamic mental model which can generate mental simulations for understanding relatively difficult transfer problems.

MULTIPLE USES OF DISSONANCE

In Susan's conceptual change cycles, the first sources of dissonance were discrepant events used to stimulate model criticism and revision. The anomalous observations provided surprises and reasons for Susan to change her model. But the experiments were not chosen only to motivate students and counter misconceptions. Each of them provides an experience which will constrain the direction of revision of a student's current model M1. Therefore, each is an instructional intervention which will influence construction of a new model M2. Susan understands that M2 must explain the experiment, but the experiences selected by the tutor will profoundly influence her ability to construct such an M2.

Each experiment was carefully chosen by the design team to point out a specific deficiency in M1, which can be remedied by adding a single new feature to that model, using ideas that were thought likely to be available within students' zone of proximal development. The purpose was to keep the dissonance as mild as possible, in order to maintain students' confidence in their ability to adapt and modify their conceptions in response to the anomalies, and thereby to maximize their chances for criticizing M1 and constructing M2 at least partially on their own.

We refer to anomalies that are chosen in this manner as "optimally discrepant events" -- to signify that they are discrepant enough to be challenging and motivate conceptual change, but not so discrepant as to be unexplainable and discouraging. The dissonance produced by such events need not be of the dismissive or confrontational kind that some would call "conflict". It can be described as a "gentle" provocation, which encourages students to venture beyond their existing view. In this case it fits the theme of model modification, rather than model replacement.

About the authors: John Clement has been engaged in research on learning in mathematics and science at the University of Massachusetts for the past 20 years. His current research is focused on methods for helping students form and use visualizable models in science. This research is enhanced by studies of mental models used by expert scientists during problem solving. He has published several books in this area as well as a large number of articles on reasoning and learning in science and math. His work has been funded continuously by the National Science foundation for the last 18 years. He has served on boards for the National Science foundation, National Science Teachers Association, and the National Science Board. In addition to his research, Dr. Clement is a Professor of Education in the area of math and science.

Melvin S. Steinberg received his Ph.D. in physics from Yale University and is Professor of Physics (emeritus since 1995), at Smith College, Northampton, MA. During the past 15 years he has been involved in research on learning difficulties and conceptual change in physics, and in curriculum development based on that research. This research has driven him to engage with the literature on conceptual change, and to study the learning paths of historically important figures in mechanics (17th century) and electricity (18th and 19th centuries). His CASTLE curriculum in electricity has been validated as a proven effective program by the Program Effectiveness Panel (US Dept. of Education), based on data from field testing in 22 US high schools (1994) and he has received grants to develop this curriculum from the Dept. of Education and NSF. He has also collaborated with John Clement in developing materials for his high school mechanics curriculum, Preconceptions in Mechanics and is presently collaborating with him in attempting to abstract principles of conceptual change from videotaped interviews of students reasoning about electric circuits with capacitors.

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