# Evolving Mental Models of Electric Circuits

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## Abstract

This is a case study of a 16 year old student, alias "Susan", discussing her thinking with a tutor during hands-on investigations of electric circuits. Susan had not studied any physics. To facilitate complex learning, her experiments were designed to foster model building in a series of small steps. Each step revised only one of Susan's alternative conceptions, so that most of her model was always available to support reasoning during an episode of conceptual change

## Strategy of instruction

In this short report we outline our model of Susan's learning process.[1] Figure 1 shows the role of three conceptual change facilitators in each step of the process.

D = Discrepant Event: challenges a single conception in the existing model

A =Analog Conception: explains the event when transferred into the model

O = Observational Link: constrains revision and supports the revised model

The large white circles in Figure 1 labelled M1, M2, M3, M4, M5 represent stages of Susan's evolving explanatory model. The small grey circles in M1 represent four initial alternative conceptions that were revised during the course of her tutoring interviews. A colour change from grey to black indicates revision to a more expert-like conception. The arrows indicate contributions to model revision, that we have inferred from video taped tutoring interviews. One consideration in designing Susan's experiments was to introduce discrepant bulb lighting events, that would conflict with her alternative conceptions. The first two discrepant events were provided by inserting a capacitor in battery-and-bulb circuits, in order to reveal the presence of a *non*-battery origin of charge and a *non*-battery current driving agent. Conflicts with Susan's alternative conceptions are represented in Figure 1 by jagged lines.

The experiments were also designed to introduce observational links that would constrain the direction of model revision by supporting the plausibility of a particular analogy. These links were provided by deflections of a magnetic compass needle that was placed under each of the circuit wires. Susan interpreted the deflections as indicating the directions of movement and rates of flow for "charge" moving through the wires of an operating circuit.

[1] A more detailed analysis, which includes Susan's development of imageable models, is given in Clement and Steinberg (to appear).



*H. Behrendt et al. (eds.), Research in Science Education – Past, Present, and Future,* 235–240.

## Diagram of model building

The video tapes of Susan's investigations and discussions with the tutor show her generating the four steps of model construction shown in Figure 1. The descriptions of these steps are expanded below, using quotes from Susan's transcript.

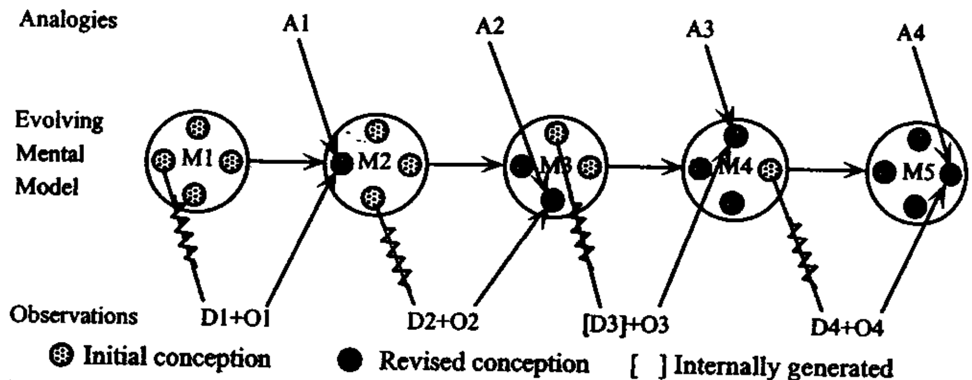


**Figure 1**

**M1**: Charge moving through the circuit wires originates only in the battery. -> **M2**: The moving charge comes also from metal in the capacitor plates.
**M2**: The battery is the only causal agent that can make this charge move. -> **M3**: Pressure in compressed charge can also make the charge move.
**M3**: NORMAL pressure in a capacitor plate cannot push any charge out. -> **M4**: NORMAL pushes charge into LOW pressure in a battery terminal.
**M4**: Flow rates into and out of a wire will be the same in all circumstances. -> **M5**: Inflow and outflow may differ, which will alter pressure in the wire.

## STEP #1 – Capacitor charging experiment (task set by tutor)

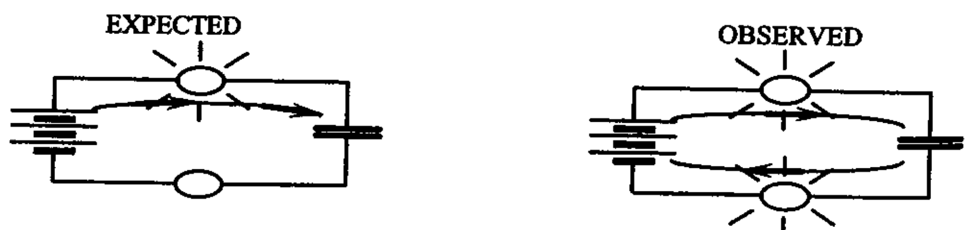


**Figure 2**

**D1** Bottom bulb lights without a conducting path to it from the top of the battery.
**O1** Flow direction implies origin in the capacitor "where it can't be coming from".

**STEP #1 – Concept Transfer** (analogy discovered by student)

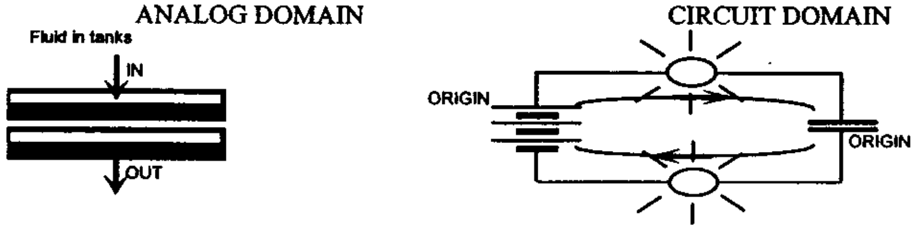


**Figure 3**

**A1** Outflow from the lower tank can occur because *the tank contains a fluid.*
**M2** Outflow from the lower plate can occur because *the plate contains charge.*

**STEP #2 – Capacitor discharging experiment** (task set by tutor)


**Figure 4**

**D2** Motion occurs without a battery to cause it: "there's no place to get it to go".
**O2** Movement is "in the other direction", in comparison to capacitor charging.

**STEP #2 – Concept Transfer** (analogy introduced by tutor)

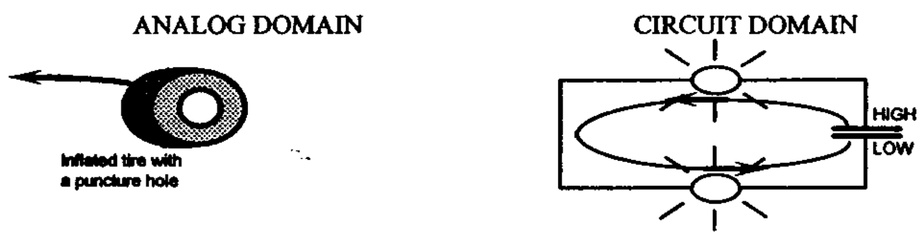


**Figure 5**

**A2** "*Pressure" in an inflated tire* will push air out through a puncture hole.
**M3** HIGH *"pressure" in compressed charge* pushes charge toward LOW.

**STEP #3 – Capacitor charging revisited** (no intervention by tutor)

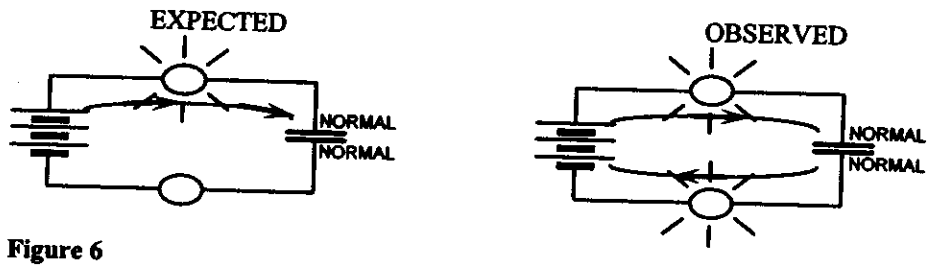


**Figure 6**

**[D3]** Lower bulb lights without HIGH pressure in lower capacitor plate causing it.
**O3** Flow direction implies agent makes flow "leave here and go to the battery".

Susan's surprise in step #3 was generated internally. We think of it as precipitated by "mentally observing" a circuit representation that now includes pressure as well as visual elements and by failing to attribute causal agency to NORMAL pressure.

**STEP #3 – Concept Transfer** (analogy introduced by tutor)

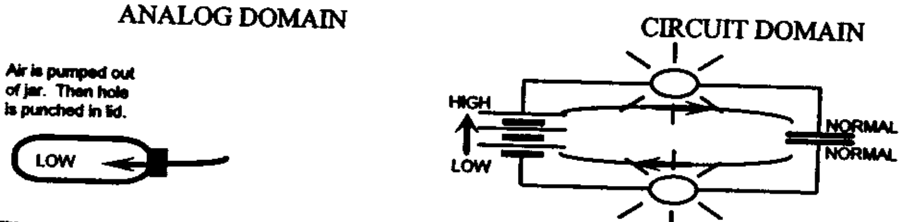


**Figure 7**

**A3** *LOW pressure in the jar* will allow NORMAL outside pressure to push air in.
**M4** *LOW in bottom end of battery* lets NORMAL in bottom plate push charge out. Battery moves charge upward, causing LOW in bottom and *HIGH in top end.*

This conceptual change episode began with Susan sensing a lack of coherence in her causal model. It ended with her adopting a revised conception of the battery as a device that maintains a pressure difference in its terminals – leading to a unified model of current propulsion in circuits based on the "electric pressure" concept.

**STEP #4 – Bulb paradox experiment** (task set by tutor)

Non-identical bulbs are connected in series as in Figure 8. The tutor introduced resistance by telling Susan that bulb A is "difficult" for charge to get through while bulb B is "easy" to get through. The tutor also provided a color code for pressure values, in which yellow is quantitatively midway between red and blue.

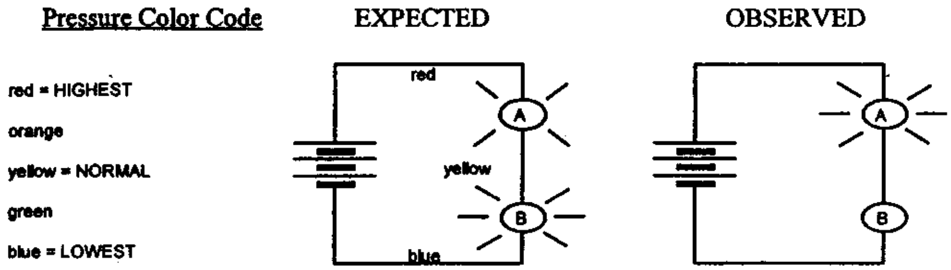


**Figure 8**

**D4** Bulb B being out conflicts with same pressure difference across both bulbs.
**O4** Same flow through A and B suggests middle wire pressure is below yellow.
Susan had to overcome her intuition that inflow *always* equals outflow for a wire.

## STEP #4 – Concept Transfer (analogy discovered by student)

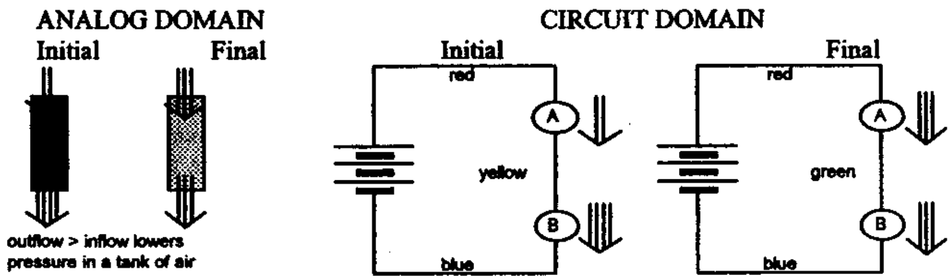


**Figure 9**

Asked what equal pressure differences across A and B would do, Susan replied:
"Less is coming in [to the middle wire] than is going out".
The tutor drew a narrow arrow by bulb A and a wide arrow by bulb B (see Figure 9).
"Would that really change the color of that wire then?"
The tutor invited Susan to say more about this.
"Whatever is coming through here [bulb A] would turn into orange. But there is more of it leaving [through bulb B]. So it overcompensates and gets rid of what would make it orange, but also takes even more away, which would turn it green. So I think that would make it green"
The tutor asked what will that do to movement in the circuit.
"You're going to have a larger push through here [A] and a smaller push through there [B]. Your arrows are going to change [to same width]."
**A4** A wire is like a tank that can have *unequal rates of inflow and outflow*. Compression or depletion will raise or lower the pressure in a wire.
**M5** Pressure change modifies inflow and outflow *until they become equal.*

Susan has now begun using electric potential – in the concrete prototype form of "electric pressure" – as *a causal-agent property of wires*, the value of which is *altered by a transient process* whenever a circuit parameter changes. She went on to use this conception to solve difficult transfer problems (Clement & Steinberg, to appear).

## Discussion

Susan never lost confidence in her ability to modify her ideas when faced with anomalies. This suggests to us that she experienced "optimal dissonance" — i.e. the anomalies were discrepant enough to motivate conceptual change, but not so discrepant as to seem unexplainable and discouraging. We believe dissonance was made optimal by three qualities of Susan's instruction:

(1) Each discrepant event was designed to falsify only one feature of her model, maximizing chances to criticize and modify the model, at least partially, on her own.

(2) The observational link in each experiment was designed to constrain the search for a corresponding feature of a new model that can explain the discrepant event.

(3) The learning environment valued incremental model modification, rather than asking her to suddenly revise her ideas all the way to the final target model.

Research on discrepant events in the seventies did not provide sufficient strategies for revising models after their limitations are exposed. Later work on revision has focused on transfer of a critical causal relationship from an analog domain. But a single analogy can be insufficiently complex. White (1989), Steinberg et al (1995) and Niedderer and Goldberg (1996) have attempted to remedy this by introducing multiple analogies for electric circuits. The present paper provides an example of how model evolution, in small steps, can exploit the power of discrepant events to motivate complex learning, while avoiding the confrontational burnout or reduction of motivation that Stavy (1991) and Smith, diSessa, and Roschelle (1993) have expressed concern about in discussing the use of dissonance in instruction.

## References

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