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Analogical Models - Boon or Bane in Science Instruction?

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INTRODUCTION

It is well established that students' preconceptions (ideas held before instruction) often pose barriers to meaningful conceptual understanding and prove to be quite resilient in the face of traditional instructional techniques. One approach which has proven effective in helping students make sense of conceptually difficult areas is the use of analogical models (Johsua & Dupin, 1987; Clement, et al., 1987; Brown & Clement, 1989; Brown, 1992a; Brown, 1992b; Brown, in press). However, the use of such models raises the question of the accuracy of the models--they may help students overcome a conceptual difficulty, but they may also encourage other kinds of misconceptions. Such critics argue that we should not be responsible for creating misconceptions, and so we should be sure that the models we teach are "correct."

There are often two related, implicit assumptions inherent in such objections. First is the assumption that teaching means authoritatively telling or otherwise communicating to students the ideas we want them to learn. Second is the assumption that whatever message we authoritatively communicate to students, as long as the "signal" is clear enough, they will receive it accurately. Under such assumptions it certainly does not make sense to authoritatively communicate to students, so that they will receive them and believe them to be true, models which we know to be misleading in some respects. However, both of the above assumptions are seriously open to question. Beginning with the second assumption, a growing body of evidence supports the contention that no matter how "clearly" and/or forcefully certain ideas are communicated, many students simply do not have the conceptual basis to assimilate the ideas in any meaningful fashion. In other words, "clarity" is a relative term depending on a person's conceptual frame of reference. As such, in contrast to the first assumption, instruction must aim to help students build on their existing conceptions rather than attempting to authoritatively transmit ideas.

Under the first set of assumptions, knowledge is conceived as a product or commodity. Once the knowledge has been hard won by the creative efforts of experts, this knowledge can now be given to students much like a television set can be given to a child with only a few instructions on how to use the knobs. Under this perspective, it makes no sense to require the child to build the television from scratch before she can watch it, for two reasons: her home-made television set is likely to be inferior, and it will take too long to build.

By contrast, the latter, constructivist perspective views knowledge as inherently the constructions of people, not as a transferable commodity which is objectively "out there," such as a television set. Engaging students in the construction of partial models makes more sense under this perspective. Although we can train students to behave in various ways with appropriate external stimuli, if understanding is the goal, students must make sense of new ideas from their own conceptual frame of reference. This is not to say that teacher-student communication is inappropriate or always ineffective, but rather that the sense the students make of this communication will depend on their existing conceptual frameworks.

Thus, critics of the use of analogical models in science instruction argue that they are often misleading, while proponents maintain they often provide a way for students to make sense of otherwise obscure or counter-intuitive ideas. We agree with both, arguing that students need to be knowingly engaged in model construction and revision in order to reap the conceptual benefits without reifying partial models. We ground this discussion in the domain of electricity (widely documented as conceptually difficult) and discuss an alternative instructional approach embodied in CASTLE (Capacitor Aided System for Teaching and Learning Electricity). The model building process in this curriculum is motivated by experiments with circuits containing batteries, light bulbs, and large capacitors. The capacitors add transient processes which give the experiments a dynamic rather than static nature and indicate cause-effect relationships which otherwise would be difficult to conceptualize. Models constructed by students through discussion of the experiments are usually valid only in limited contexts. The failure of these partial models in new contexts is exploited to stimulate criticism and revision toward a more expert model. We argue that this incremental, experience-driven, model revision process is necessary (versus prematurely giving students a full-blown expert model), since students' intuitive knowledge at a deep level must be reconstructed.

We first examine this model revision process as embodied in the CASTLE curriculum, focusing in particular on the concept of electric potential. We then look at some parallels between the models in the CASTLE curriculum and historical models. Although CASTLE was not originally developed to recapitulate historical models, there are some striking similarities. We then present evidence that the model construction and revision process is more effective than traditional approaches and explore more closely the model revision process in a case study of a student learning using the CASTLE materials.

A CURRICULUM TO ENGAGE STUDENTS IN MODEL CONSTRUCTION

Recently reported data make the case that very few students are able to reason with the electric potential concept after instruction in college physics courses (Steinberg & Ofcarcik, submitted). This conclusion is supported by a large body of earlier research on students' conceptual difficulties in electricity (Cohen et al., 1983; Closset, 1983; Duit et al., 1985; Shipstone, 1988; McDermott & Shaffer, 1992; Millar & King, 1993). We suggest that much of the problem is due to the abstract mathematical approach to the electric potential concept that is broadly favored by the physics teaching community. In this article we describe an alternative approach taken by the Capacitor-Aided System for Teaching and Learning Electricity (CASTLE).

The CASTLE Project is a materials development effort by a team of 15 high school and college physics teachers with support from the National Science Foundation, which builds on earlier explorations of capacitor-controlled bulb lighting as a way of stimulating model construction

(Steinberg, et al., 1993[1]; Steinberg, 1983, 1985, 1987a; Steinberg & Wainwright, in press). CASTLE teacher and student manuals for high school physics courses (Steinberg, 1987b), and a student equipment kit have been field tested and are now available commercially.[2]

"Electric potential" is given meaning in the CASTLE curriculum through hands-on investigations that stimulate students to engage in a process of confronting misconceptions and mobilizing useful intuitions to construct a sequence of increasingly general models of current propulsion in circuits. The goal of this process is a visualizable expert model which unifies circuit and electrostatic phenomena through a conception of electric potential that can be used effectively in qualitative reasoning.

Part A describes experiments with high-tech capacitors charging through miniature light bulbs, which help students construct a model of mobile charge in conductors as a reversibly compressible substance which is being pumped out of one capacitor plate and compressed into the other. These experiments stimulate conceptualization of electric potential intuitively as "electric pressure" in the compressed charge--like air pressure in compressed air. "Electric pressure" is the causal agent that terminates charging and initiates discharging.

Part B describes the use of capacitors in series to suggest distant action and to prompt the need for two model revisions: (1) Add a "halo" (scalar field) of "potential electric pressure" (electric potential) in the space around a charged conductor. This is envisioned as latent "electric pressure" which is experienced as actual "electric pressure" in a nearby conducting test body.

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[1] This curriculum guide contains a Teacher Resource Manual and a self-paced Student Manual which is intended for duplicating and distributing in class. It is written for typical American high school physics classes. (Versions for other student populations may be written in the future.) Developed with support from NSF grant MDR-9050189.

[2] The CASTLE Equipment Kit, containing materials required for a pair of students investigating circuits of light bulbs and capacitors (0.025 farad capacitor included), is available from PASCO Scientific. Required auxilliary equipment -- Genecon mini-generator and 0.1 farad capacitor -- is also available from PASCO. The specially designed capacitors are non-polar and have negligible internal resistance.

(2) Add <u>negative</u> charge, the source of a halo of <u>low</u> "potential electric pressure." The lighting of a neon bulb by a pie-plate capacitor placed near rubbed insulators confirms the revisions and applies them to all matter.

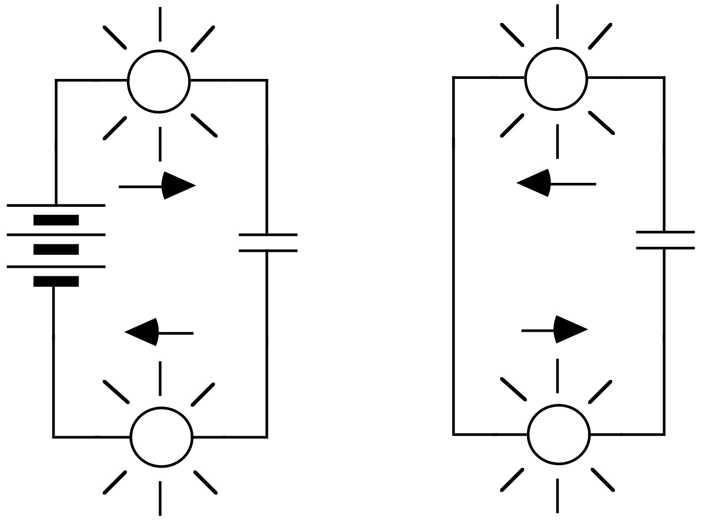
Part C briefly discusses the historical foundations of the "electric pressure" concept from a cognitive process perspective--its origin in Volta's eighteenth century pneumatically-modeled "electric tension" concept, and the fate of Volta's attempted revision toward a more general conception that includes electrostatic distant action.

Part A - Constructing an Intuitive Foundation Model

Three of the CASTLE instructional interventions that stimulate students to invent an intuitive conception of electric potential are presented below. The first two exploit the fact that bulb lighting in a circuit with a capacitor is occurring in a circuit that is broken by the insulating barrier between the capacitor plates. One of the plates is visualizable as a site of origin of whatever is moving through the circuit, and the other as a site of destination where compression occurs.

1. Non-battery origin of the moving charge

Figure 1 shows directions of movement in the upper and lower parts of a circuit during capacitor charging and discharging. The directions are determined by a compass (not shown) placed under each wire. The compass deflections show movement out of the lower capacitor plate during charging and reverse flow during discharging. The flow out of the lower plate during charging indicates that what is moving does not originate exclusively in batteries (as nearly all students believe) but is also a constituent of the ordinary conducting matter of which capacitor plates (and wires) are made. From a macroscopic point of view, any conducting body may therefore be thought of as being filled with mobile charge.



Capacitor Charging Capacitor Discharging

Figure 1

2. Charge compression in a capacitor plate

Most students think of the mobile charge that is normally present in conducting matter in terms of a water analogy. But a second experiment demonstrates that it can be compressed in a capacitor plate, and so behaves like air in this respect.[3] This conclusion results from charging a capacitor and then, after it becomes "full," adding a second battery to "push harder"--as illustrated in Figure 2.

Students understand that air which has been blown into a balloon and then comes back out through a puncture hole is driven out by a condition in the compressed air called "air pressure." This construction, which is rooted in sensory experience, enables them to conceptualize an analogous causal agent which during discharging drives charge back out of a capacitor plate into which it was compressed during charging. The causal agent operating in the analogical model can be compellingly described as "electric pressure" in the mobile-charge fluid contained in the plate.

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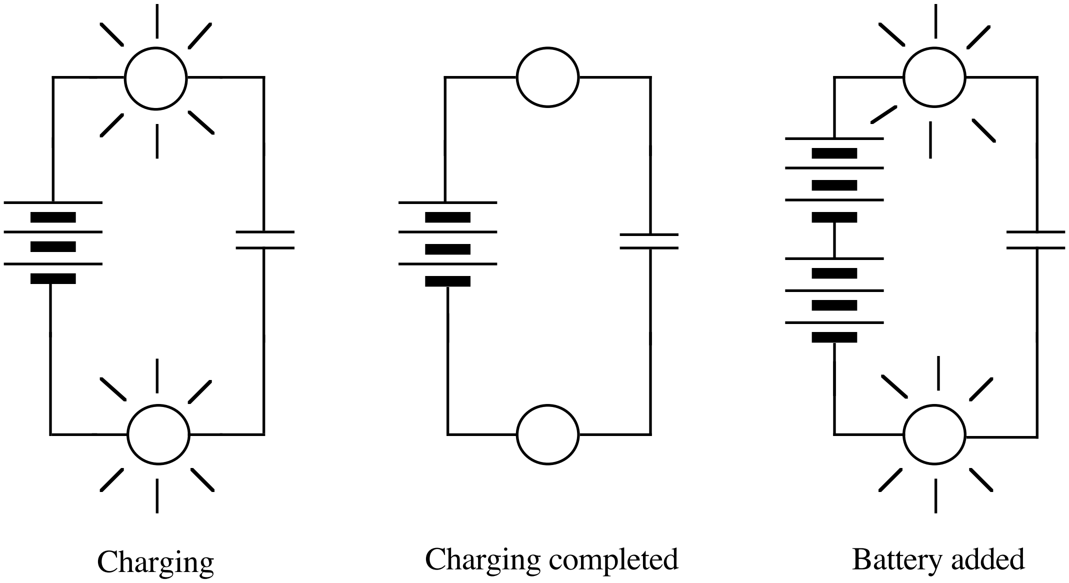
[3] Physics books do not speak of compression, but their representations are fully consistent with the concept. Consider the formula giving the electric potential V in a conducting sphere of radius R containing excess charge Q. In suitable units this may be written $V = Q/R$, which says the potential may be increased in two ways: (1) push more charge in or (2) shrink the radius.

"Electric pressure" is an operational equivalent of electric potential in conducting matter. This non-standard term is extremely useful, because it keeps the analogy to air pressure constantly in mind and thereby helps students retain a sense of connection between electric potential and familiar sensory experience. Students are able to use this highly intuitive concept early-on for effective reasoning about circuits containing one capacitor--or none--in series with the conducting circuit components.


Charging

Charging completed

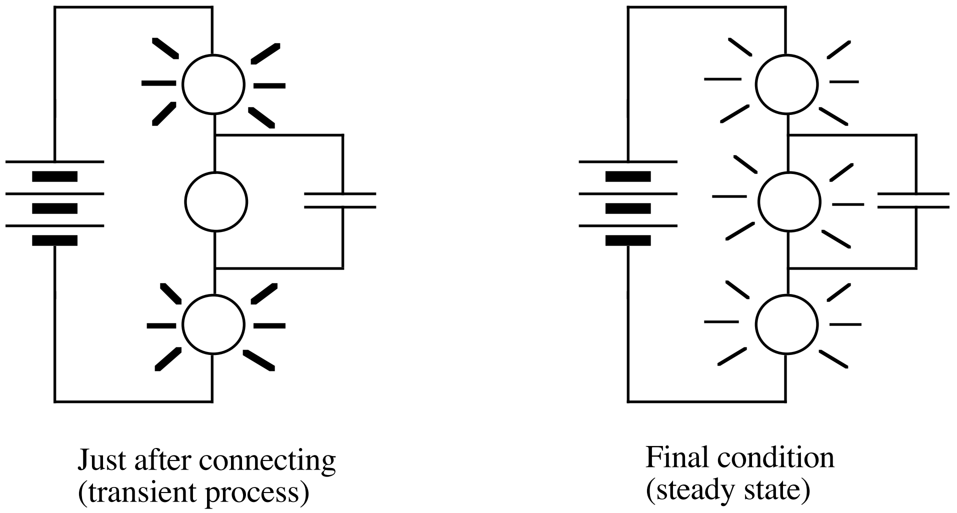
Battery added

Figure 2

3. "Electric pressure" in the connecting wires

Students need to understand that "electric pressure" exists in wires as well as in capacitor plates, and that different values in different wires are a consequence of different degrees of compression/depletion <u>in the wires</u>. But they tend to think of wires as pipes--not as tanks, like capacitor plates. It is difficult to address this conception directly, because such a tiny amount of charge displacement is required to cause a few volts "pressure" difference in the wires connected to a bulb. The amount can be made enormously larger, however, by connecting a capacitor in parallel with a bulb as in Figure 3.

Only the top and bottom bulbs light up immediately after the battery is connected in this circuit. The middle bulb remains dark until there has been enough inflow/outflow through the top/bottom bulb to raise/lower the "pressure" in the top/bottom capacitor plate by a significant amount. When a smaller capacitor is substituted, the middle bulb remains dark for a shorter time. Students can readily understand that much less added/depleted charge is required to raise/lower the "pressure" in a tiny wire than in a very large plate-plus-wire metallic region. (Think of the amounts of air needed to raise the pressure by a given amount in a tiny balloon and in a very large balloon.)


Just after connecting
(transient process)

Final condition
(steady state)

Figure 3

Students tend to focus on the "pressure" difference in the capacitor plates as the agent of current propulsion through the middle bulb. But they can be helped to consider that the wires connected to the bulb are also sources of this "pressure" difference.

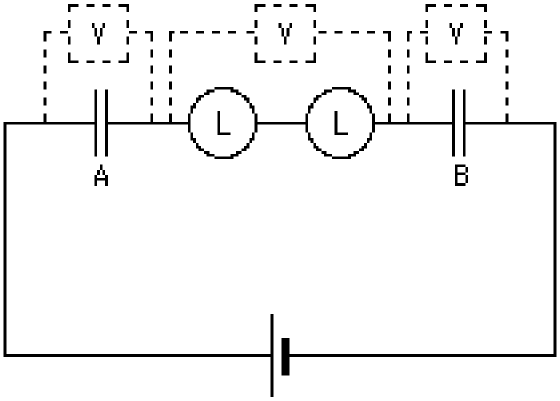
On removing the capacitor from the circuit after steady-state flow has been achieved, they will observe that there is no change of bulb brightness. This implies that charge flow through the bulb is being driven by a "pressure" difference in the wires connected to it. The observation also implies that the transient process preceding the steady state will compress/deplete charge in the wires in just the amounts needed to make "electric pressure" differences in the wires drive the same final steady-state flow rate through all series circuit components.

Part B - Revising Toward a Visualizable Expert Model

Three of the CASTLE instructional interventions that stimulate students to criticize the intuitive foundation model and revise it toward an expert model are presented below. Charging two capacitors in series indicates electrostatic distant action in circuits, which suggests adding a scalar field and negative charge to the pneumatic model. Bulb lighting by a home-made capacitor placed near electrified insulators is exploited to confirm the model revisions and unify circuit phenomena with the electrostatics of insulators.

1. Criticizing the intuitive foundation model

The pneumatic foundation model predicts there will be no lighting for the bulbs in the circuit of Figure 4, because the two capacitors isolate these bulbs in a "conducting island" which cannot be influenced by the "pressure" in circuit components outside the island. The fact that the bulbs actually do light (transiently) indicates the need for a model that includes distant action--across the spaces between the capacitor plates. The voltmeter measurements indicated in Figure 4 provide additional information that helps guide revision of the model toward greater adequacy.



The "conducting island" experiment

Figure 4

2. Revising the model to include distant action

The CASTLE curriculum suggests to students that the distant action implied by the conducting island experiment can be explained by something <u>outside</u> a charged conductor which extends the influence of its charge into the ambient space and enables it to influence the "electric pressure" in distant conducting bodies. The global pattern of this external something is called a "halo." The halo is assumed to move with its source charge wherever the charge goes. It is also assumed to be something non-material which can penetrate material objects and be penetrated by them.

What does the halo consist of, that enables it to influence distant conducting bodies? Students are asked to assume that the halo is a seat of <u>latent</u> "electric pressure"--a property that is experienced as <u>actual</u> "electric pressure" by a conducting test body placed within the halo. The CASTLE term for this property is "potential electric pressure." After students have become proficient at using "potential electric pressure" to predict and explain distant-action phenomena, this term can be replaced without confusion by the much less suggestive but more professional "electric potential."

The suggested conception predicts that the left hand bulb in Figure 4 lights because: A halo of <u>high</u> "potential pressure" around the excess charge at the (+) battery terminal not only raises the "pressure" at the left of capacitor A; it also spans the insulating gap and raises the "pressure" on the other side of capacitor A. This prediction is verified by a null reading of the voltmeter across capacitor A when capacitor charging first begins.

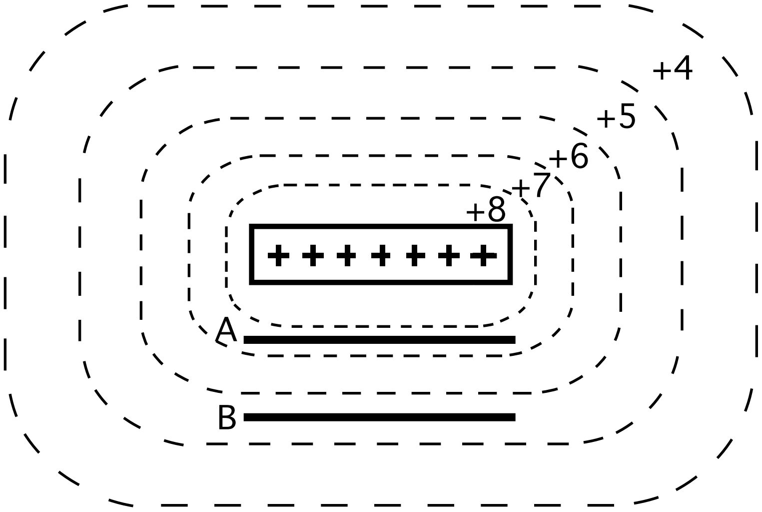
Lighting of the right hand bulb in Figure 4 is hypothesized to occur because: There are two kinds of charge, which have opposite effects that cancel out if both are present in equal amounts. Depletion of "positive" charge at the (-) battery terminal not only lowers the "pressure" at the right of capacitor B; the resulting excess of "negative" charge also is the source of a halo of low "potential pressure" that spans the insulating gap and lowers the "pressure" on the other side of capacitor B. This prediction is verified by a null initial reading of the voltmeter across capacitor B.

The idea of pressure lowering by negative charge can be made easy to grasp by offering students a familiar thermal analogy: A flame raises the temperature in a nearby test body (e.g. one's finger), but an ice cube has the opposite effect.

The "potential electric pressure" in the halo around an excess of either kind of charge is assumed to be gauge "pressure"--not absolute. This idea can take some time for students to accept, but it is necessary in order to explain the fact that uncharged capacitor A is high on both sides while uncharged capacitor B is low on both sides when charging first begins. It is assumed that this gauge "pressure" decreases with distance from the source charge--an intuitive idea for students.

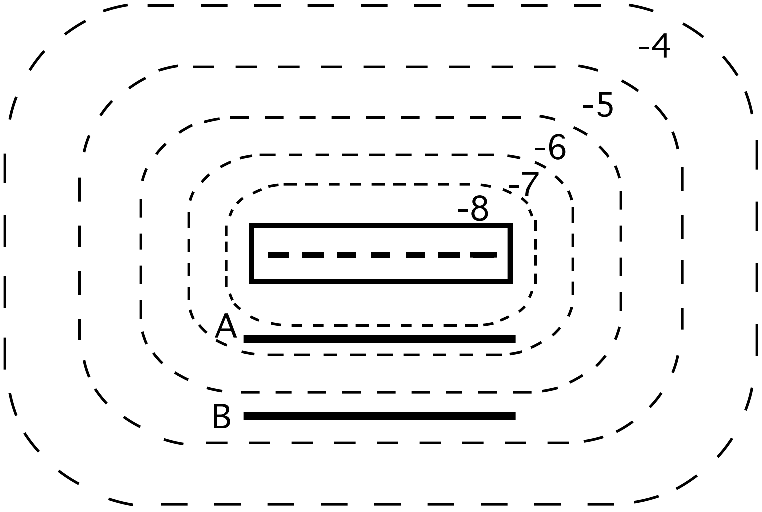
Figure 5a illustrates the conception of a halo of "potential pressure" around a positively charged plate, with a nested set of equipotential curves (dashed lines) with positive numbers indicating high gauge "pressure" which decrease with distance from the plate. Figure 5b illustrates the halo around a negatively charged plate, with low gauge "pressure" indicated by negative numbers which become less negative with distance from the plate.

The short heavy lines labeled A and B in Figures 5 (a and b) represent metal plates in which actual gauge "pressure" values will be determined by the positions of the plates in the halo. These will be ignored for the moment.



"Potential pressure" halo around excess charge

Figure 5a



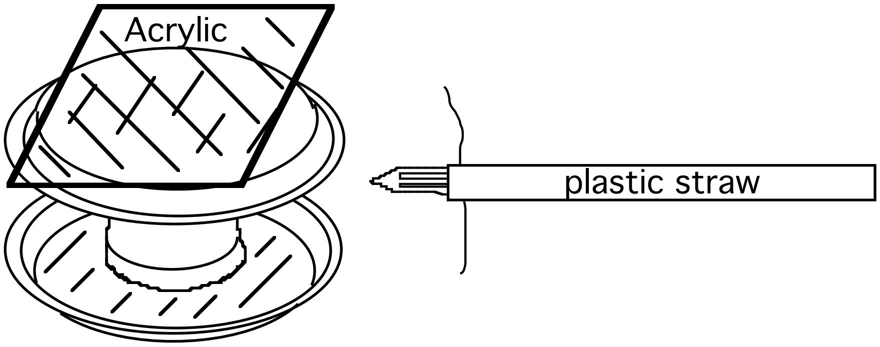
"Potential pressure" halo around negative source charge

Figure 5b

3. Testing the revision with charged insulators

The idea of two kinds of charge in conducting matter, with one kind mobile and the other not, raises the question whether (+) and (-) charge is also present in insulating matter but with <u>neither kind mobile</u>. If that were true, then rubbing bodies made of different materials on each other might result in some of one kind being transferred from one body to the other. It would leave the two bodies oppositely charged, and thus surrounded by halos with high and low "potential pressure" as illustrated in Figures 5 (a and b).

Students carry out the experiment by placing a home-made pie-plate capacitor near a rubbed piece of insulating material--for example, near the acrylic (which has been rubbed on a plate of Styrofoam) shown in Figure 6. According to the revised model, this will induce higher actual "electric pressure" in the upper metal pie plate if the acrylic has excess (+) charge lower "electric pressure" in that plate if the acrylic has an excess of (-) charge. When a neon bulb is connected across the metal pie plates as illustrated in Figure 6, the existence of an "electric pressure" difference between the pie plates should drive current through the bulb. The flow should also be downward/upward for +/- source charge on the acrylic. The predicted bulb lighting is observed. The predicted reversal of flow direction is observed when the acrylic is interchanged with the foam on which it has been rubbed--detected by neon light emission from the opposite electrode.



Electrified acrylic near top pie plate

Neon bulb detector held in plastic straw

Figure 6

This experiment provides a compelling confirmation of the "potential electric pressure" halo model of electrostatic distant action. It also provides evidence that (+) and (-) charge are present in insulators as well as in conductors, with the crucial difference that neither type is mobile in insulators. The experiment relates concepts developed for circuits of conducting matter to situations involving electrostatic distant with conducting <u>and insulating</u> bodies.

The non-standard CASTLE term "potential electric pressure" is very useful, because it allows students to shift from thinking about "pressure" in a fluid model to "potential pressure" in a distant-action model without having to give up the association with air pressure. The association of "<u>potential</u> pressure" in empty space with <u>actual</u> "pressure" in conducting matter helps anchor "electric potential" intuitively--in experiences with air pressure--as the causal agent of <u>all</u> electrostatic action.

The mobility of the halo images makes it easy to for students to superpose them, and to discover visually that <u>flat</u> charged plates must have <u>linear</u> halos in order to form a capacitor with <u>uniform</u> "pressure" in the connecting wires. Experience suggests that superposing these scalar field patterns is less difficult for students than has been reported for vector electric fields (Steinberg & Wainwright, in press). This may be because there are familiar topographic, thermometric, and barometric models of nested sets of equal-value surfaces associated with movement of something from high to low values, whereas there are no intuitive models for a non-material vector field.

Part C - Historical Foundations of "Electric Pressure"

Critics often ask why the CASTLE initial explanatory model uses an air analogy, rather than the more familiar water analogy. There are two reasons why air provides a more attractive analogy for charge flow than does water: (1) The compressibility of air is palpable, and that of water is not, thus the air analogy makes it vastly easier for students to visualize compression of charge and the resulting effort-to-expand called "electric pressure." (2) A charged capacitor discharges <u>spontaneously</u>--the effect of an <u>internal</u> causal agent which is a property of the compressed charge itself--whereas water must be driven by gravity in order to obtain perceptible flow. There is evidence that such a model was also important in the historical development of the idea of electric potential, perhaps for similar reasons.

1. Eighteenth century origins

The electric potential concept is the product of a research effort which began in the eighteenth century, when electrometers became sufficiently sensitive to reveal different instrument deflection for conductors of different size which had been given equal amounts of excess charge. The ontological question was: What was the instrument deflection measuring? What kind of property of a charged body might depend on, yet be distinct from, the amount of excess charge?

In 1778 Alessandro Volta began to visualize electrified conductors as containers of a compressible substance, and to conceptualize the property measured by an electrometer as an outward-pushing pressure-like condition in the substance which he called "electric tension":

> The energy which I call electric tension is the effort [of the compressed substance] to push itself out. (Academia Nazionale dei Lincei, 1918, p. 213)

This is essentially the same conception of electric potential in conducting bodies that is intuited by students in a CASTLE classroom.

Henry Cavendish employed a similar model in 1771, in which he made explicit use of the analogy to compressed air and invented a concept much like Volta's which he (unfortunately) called "electrification" (Maxwell, 1879, p. 195). The fact that both of these pioneers of modern electricity concepts found their way to the same intuitive idea suggests the power of the pneumatic analogy as a starting point for understanding the electrostatics of conductors.

Volta's earlier research on gases is thought to have played an important role in stimulating him to construct a pneumatic analog model. His use of "tension" rather than "pressure" appears to have come from focusing on the instrumentation rather than on the substance being investigated. (The medical term "hypertension" reflects a similar focus in relation to "high blood pressure.") In any event, his defining phrase ("the effort to push itself out") suggests that his "electric tension" is used like pneumatic pressure.

Volta attempted to modify his compressible fluid model so that it would account for distant action as well as for effects in conducting bodies. When a charged disk A is brought near a conducting disk B, he wrote:

> The electric fluid in B ... increases as much in expansive force as air does in a container of normal density when it is heated. (Academia Nazionale dei Lincei, 1918, p. 244)

In this passage Volta comes close to making the CASTLE transition from "electric pressure" to "potential electric pressure." But he did not posit latent "electric tension," the agent that extends the influence of charge into the ambient space. Instead, he tried to explain distant action by envisioning charge (which raises "tension" in a conductor) as an analog of temperature (which raises pressure in air). Volta's very interesting attempt at model revision did not lead anywhere because the field concepts he was groping toward were not available in 1778.

2. The research and education agendas

Volta's "electric tension" concept was widely accepted well into the nineteenth century. It still survives among engineers, who occasionally speak of "high tension wires," but was abandoned by scientists after about 1850. At this time the electrical potential function, introduced by Poisson in 1811 as a formal analogy to Laplace's gravitational potential function, predicted uniform electric potential in conducting bodies (equivalent to uniform "electric pressure") and much more: (1) the presence of excess charge only on the surface of the conductor, (2) the existence of variable electric potential in the exterior space, (3) the Newtonian force on a test particle. The greater scope of this abstract mathematical model made it much more useful for the research agenda of the mid-nineteenth century.

But what worked well for expert practitioners bound to the research agenda was a loss for science education, because very few students are able to reach its stratosphere of abstraction in one grand leap. The education agenda has since 1850 retained the research agenda as its own. We have an obligation to help novice students find a path from their initial conceptions to the abstractions of expert models. The CASTLE curriculum provides a way to reopen the first half and complete the last half of Volta's path in the interest of the education agenda.

STUDENTS' RESPONSE TO MODEL CONSTRUCTION

Diagnostic Data

Large scale diagnostic testing provides some evidence for improved understanding by engaging students in model construction, criticism, and revision processes in the CASTLE curriculum. A multiple choice diagnostic test was administered before and after instruction (an identical pre and post test) to three groups of students--experimental, dissemination, and comparison. Students were included in the sample only if they took both the pretest and the posttest. All groups had representation from various geographical areas across the United States. The experimental group consisted of students of the teachers who used the CASTLE materials and who were involved in the authoring of the materials. The dissemination group consisted of students of teachers who were given the materials with minimal instruction (typically 1-2 hours by one of the experimental teachers). The comparison group consisted of students of teachers who did not use the materials, but who did teach electricity.

The diagnostic was constructed without reference to the materials used in instruction, and all teachers administering the diagnostic were blind to the contents of the test. Although the CASTLE curriculum involved significant use of capacitors, the situations in the diagnostic employed only batteries, wires, bulbs, and single switches, since these would be familiar to comparison students as well. The questions asked about situations which would tend to draw out known alternative conceptions. For example, a student reasoning sequentially would tend to predict that the shorting of a "downstream" bulb would not affect an "upstream" bulb since the current already passed the upstream bulb.

Although data from the third year of administration of the diagnostic have yet to be analyzed, data from the first two years indicate that students using the CASTLE materials (both experimental and dissemination groups) had significantly larger gains from the pre-test to the post-test than comparison classes (Brown 1992b). However, these gains were not as large as they could have been, even though the partial model of the battery as a pressure source for single fluid electricity would have been adequate to answer all of the questions. An hypothesis here is that while the materials were significantly more effective than traditional instruction at engaging students at a conceptual level, students' prior conceptions were too deeply entrenched, sabotaging understanding of even a partial model. While data are not available to support or refute this hypothesis for the students taking the diagnostic test, the hypothesis is upheld in a tutoring study in which students were individually instructed using the CASTLE materials. We examine a case study of one of these students from the perspective of a framework for interpreting students' conceptions.

Framework for Interpreting Students' Conceptions

Brown (1992c) hypothesizes four different "lenses" through which we can view students' conceptions--verbal-symbolic knowledge, conscious models, implicit models, and core intuitions--discussing these as different ways of looking at what are presumably different kinds of conceptual components. Verbal-symbolic knowledge is considered to be discrete, intentionally employed, and generally specific to a particular domain. Conscious models are considered to be analog, intentionally employed, and domain specific. Implicit models are considered to be analog, automatically employed, and domain specific. Core intuitions are considered to be analog, automatically employed, and domain general.

In this framework, students' conceptions are considered to be ensembles of components at different levels. Thus, conscious representations (verbal-symbolic knowledge and conscious models) will often (if not always) be attached to and influenced by unconscious components (implicit models and core intuitions). In such cases, representing students' conceptions as purely propositional or consciously imagistic will be misleading, since the subliminal influences of implicit models and core intuitions will be ignored.

While different authors often focus on one level in reported research, Brown (1992c) hypothesizes that multiple levels are involved in conceptualizing and that a complete characterization of students' conceptions will involve characterizing components at these various levels, as well as interactions between the components. Ideas from this framework are used in interpreting the following case study.

Tutoring Case Study

Brian was interviewed five times, approximately once per week for one hour each session. In the first and last sessions he was asked conceptual questions to examine his conceptions before and after instruction. The middle three sessions were instructional, attempting to establish the intuitive foundation model described above. Brian was described by his teacher as intelligent and one of her best students, and his protocol shows a willingness and ability to construct and evaluate models. He thus provides a very interesting case study of the processes involved in this kind of learning. However, even though he was able to understand and work with various models, and his use of models increased in sophistication, there were a number of instances of regression to prior ideas. Two of these are discussed below.

With regard to his conception of the battery, initially Brian stated confidently that the charge comes only from the battery. During the instructional interviews, Brian considered a number of situations that brought into question his conceptions of the battery as the sole source of charge and of current consumption in the bulbs. For example, arguing against current consumption were observations that the bulbs light just as brightly during discharging of a capacitor as during charging. If the bulbs used up charge, the bulbs should be dimmer during discharging. This seemed convincing to him, and he accepted the idea of the bulbs as "hard places to get through," with the heating and consequent lighting resulting from something akin to friction as the current passes through.

Opposing the idea of the battery as the sole source of charge were experiments indicating that the charge for some bulbs must be coming from one of the capacitor plates. He seemed to understand that a capacitor provides a break in the circuit since he indicated that bulbs should not light with a capacitor in the circuit since the circuit was not complete. However, at the beginning of the fourth interview, Brian indicated that his father (an electrical engineer) had told him that a little current jumps across the plates. He later remembered that his father had told him that the charge which lights the bulb after the capacitor comes from the capacitor plate, but he seemed so guided by his conception that charge can only come from the battery that direct instruction from both the interviewer and his father was distorted to fit his conception.

As another example of regression, the conception of the battery as the sole source of charge remained strong enough to dethrone the pressure theory at the end, even though he was able to articulate the pressure theory fairly well. This transcript segment is from the interview at the end, when the interviewer was not tutoring any more but was simply probing for his understanding.

I: Where do the charges come from?

B: I'd say from the battery, but just like we were talking last time you were saying that was a source of pressure more than a source of charge, but, hmm, I'd say the battery's still, unless the charge is always in the wires and the battery just causes it to be drawn through...I'll say the battery. Even though last session I had kind of decided that that was the source of the pressure--maybe not that the charge comes from the battery but that the battery causes the--ahhh, now I'm all confused.

I: What are you thinking?

B: Before that last session I would have always said it was just from the battery, but we kind of decided that the battery was a source of a kind of pressure, you would say the pressure theory, the battery causes the charges to be drawn through the light bulb, so I don't know if it comes from the battery, so I, but the charge may be just in the wire kind of, or else, well, hmm, yeah I'll go ahead and say they're from the battery cause see, part of this battery's positively charged and this is negatively charged so that therefore when this is connected up, these two ends are connected, then the, this is drawn to the negative end so it just basically moves from here [positive end] to the negative end.

I: Ok, so before this is connected up are there any charges in the wires or not?

B: Well, before it's connected to the battery at all I'd say there's not.

He then goes on to propose that the wires are initially empty, but the battery squirts charge into the wire when it's connected, so that charge would be in the wire if the wire were disconnected after being connected. As shown in Figure 7, this model seems to be connected to three implicit models which exert a subliminal influence on his thinking: 1) wires guide flow, much like a river channel guides the flow of a river; 2) baterries are the cause of the flow; and 3) flow is like water from a hose (i.e., unconstrained, therefore what happens downstream does not cause back pressure affecting what happens upstream). These implicit models are connected to the domain independent core intuitions of inertness (O), initiating agency (-->), and initiated agency (--]), respectively (Brown, submitted). An inert entity is not considered to be affected by impressed agency (i.e., causal power) nor to possess any agency itself. For example, a brick wall may often be considered in this way. While the inert entity is not considered to initiate, react to, transmit, or accept transmission of agency, its presence can provide a barrier, constraint, or resistance to agents. An initiating agent is independently capable of causing because it has its own source or store of agency. For example, batteries can initiate current flow, and baseball players can throw or bat balls or cause their own motion. An initiated agent is capable of causing because it has been empowered by another agent (i.e., agency has been transmitted to it). For example, a thrown baseball can knock down bottles, as can water squirted by a hose.

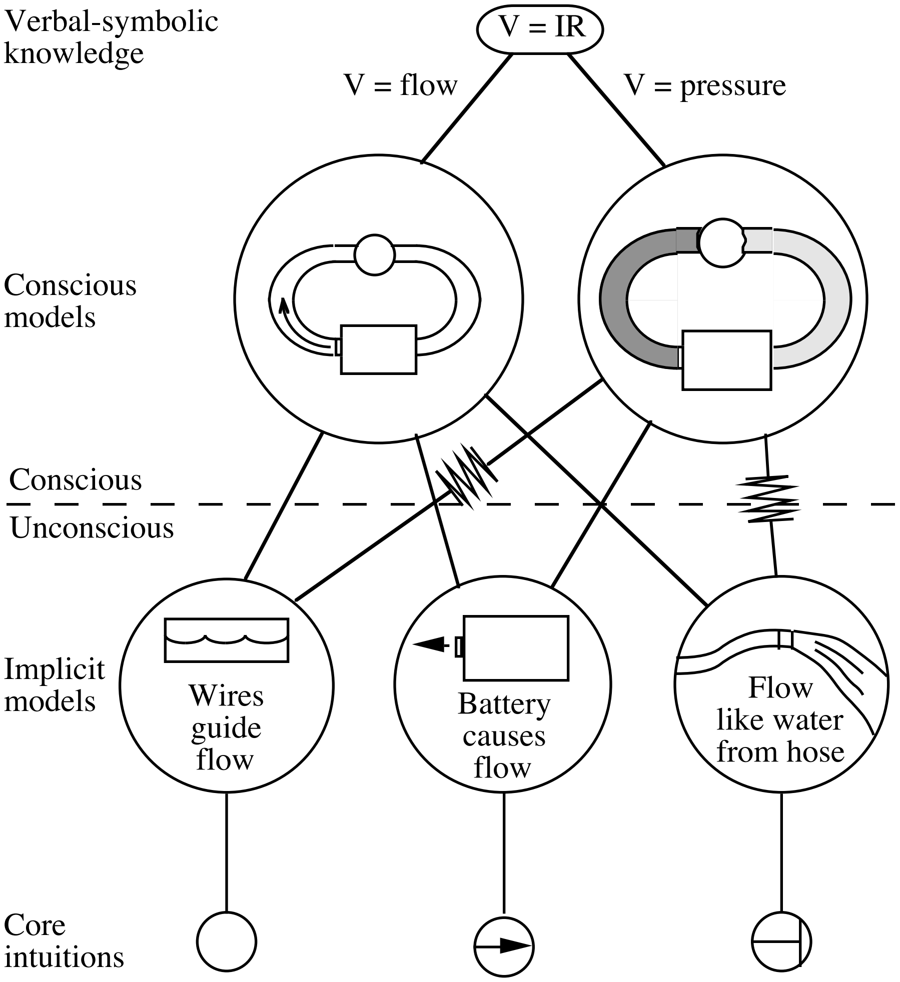


Figure 7

Both conscious models (battery squirting charge into the wires and battery drawing through charge already there) are consistent with the implicit model of the battery as the cause of flow, but the latter model is inconsistent with the first and third implicit models which imply that the flow is caused by the squirting of the battery, not by pressures internal to the fluid itself, since the fluid in the wires does not fill the wires, it simply flows along like water in a river channel or a sewer pipe after being squirted out by the battery.

However, Brian did grow in sophistication in his use of models by constructing a "synthetic model" (Vosniadou and Brewer, 1992) which was consistent both with his implicit models and with his conception of the pressure theory. In discussing two bulbs in series, he talked about charge being "backed up." In this model, wires are initially empty pipes, but they are filled up with charge from the battery and some charge gets "backed up" at the bulbs since these are tight places to get through. His accompanying drawing shows +'s (representing charges) throughout the wires, but with a higher density of +'s before a light bulb. Thus, there is less current after a bulb than before it, but all of the charge eventually gets through (see Figure 8).

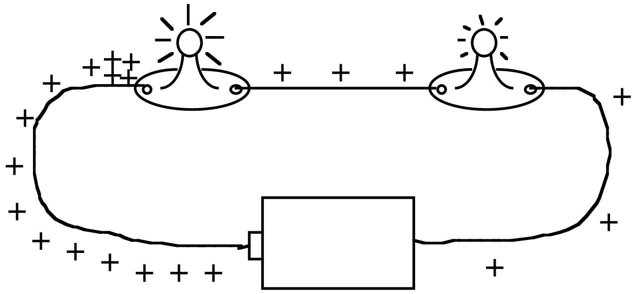


Figure 8

Brian was constantly trying out new models and tentatively accepting or rejecting them based on new or remembered evidence. However, he was also strongly guided by implicit models and core intuitions which colored his interpretations of experiments and often distorted attempts at direct instruction. As can be seen from the final interview, these conceptions were strong enough to dethrone the model of the battery as a source of pressure acting on charge present throughout the circuit. Until the end he maintained that the battery was the sole source of charge, although his later models incorporated some aspects of a pressure theory.

Brian did make some progress as a result of the tutoring. He moved from a clearly articulated battery autonomy model to a hybrid between the battery autonomy model and the battery as a pressure source model. He also abandoned the idea that charge must be used up in the light bulbs. However, there was evidence of deeper, unconscious elements undermining or corroding the conscious models constructed during instruction. For example, in the third session he conducted several experiments, which he indicated were convincing, showing that the charge to light the bulb downstream from the capacitor must come from the capacitor plate. However, in the fourth session he maintained that charge comes from the battery and goes through the capacitor to light the bulb after the capacitor. He even maintained that his father (an electrical engineer) had told him this, when in fact he had told him that charge comes from the capacitor plate, as he eventually acknowledged. Further on in the fourth session, he seemed to agree strongly with a model of the battery as a pressure source. However, in the fifth session, although he articulated the idea of the battery as a pressure source with charge initially throughout the circuit as a possibility, he rejected this as implausible. This can be accounted for by the implicit models of the flow of charge as squirting into open pipes which provided guidance for the flow but not constraint to hold it under pressure. These implicit models seemed to sabotage his emerging understanding of the battery as a pressure source. In the final interview, he articulated the possibility of charge being initially present throughout the circuit, but he rejected this as implausible. Thus, subliminal implicit models and core intuitions proved both influential and tenacious.

DISCUSSION

The argument against the use of analogical models in instruction is usually one of accuracy--they will be misleading in some ways if pushed too far, as any analogy will break down eventually. This will lead to misunderstandings either during present instruction from overgeneralization of a limited model, or it will lead to difficulties further on in the student's studies as it will lock the student in to a limited model. However, an implicit assumption in focusing on content accuracy seems to be that the content is objectively there in the words and diagrams representing the model. By contrast, if knowledge is viewed as fundamentally the constructions of people, then the question is not whether a <u>scientist</u> would say the model does or does not violate her understanding of the topic, but rather whether the model would help a <u>student</u> move closer to the scientist's understanding.

As the diagnostic evaluation of the CASTLE project indicates, this instructinal approach does seem to be able to move students closer than conventional approaches to the scientists' understanding. Further, as the discussion of the materials themselves indicate, the analogical models can be modified or "upgraded" in future model criticism and revision cycles to help the student achieve a quite sophisticated conceptual understanding of electricity. Thus, engaging students in such model construction, criticism, and revision <u>can</u> be instrumental in helping students grow from their initial intuitions to a rather sophisticated conceptual understanding.

However, although in each of the instances presented here (CASTLE, historical ideas in electricity, and the case study of Brian), the use of model construction and revision did result in some advances in understanding, these advances were invariably slower or smaller than might be expected. Contrary to the expectations of critics, even "simple" models are neither assimilated easily nor wantonly overgeneralized. Brian's case study gives us a glimpse at the conceptual "thorny ground" that these models must contend with and provides a strong argument against initially introducing expert models. These have resulted from a long process of model construction, criticism, and revision as scientists have struggled to readjust their own intuitions to make sense of the models, resulting in models that are quite distant from the implicit models of most students.

For these reasons we conclude that the use of analogical models can be an invaluable aid in instruction, under certain conditions: 1) they help students develop understandings which would otherwise be difficult to achieve by providing mentally manipulable images which are anchored in appropriate intuitions; 2) they can be modified or adapted in later instruction to help with (or at least not hinder) more sophisticated ideas; and 3) students are knowingly engaged in the model construction, criticism and revision process. When these conditions are met, analogical models can be a powerful aid in helping students make sense of the many counterintuitive ideas in science.

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