ANALYZING THE USE OF TEACHING STRATEGIES IN A MODEL BASED CURRICULUM: PROMOTING EXPERT REASONING AND IMAGERY ENHANCEMENT IN HIGH SCHOOL STUDENTS[1]

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We wish to document the use of important teaching strategies and to cast them in a form that will optimize their usefulness for teachers and curriculum developers. From expert think-aloud protocols, we have identified a number of strategies for evaluating and modifying explanatory mental models. Analyzing a model-based high school science curriculum to see whether this set of strategies might apply, we document the use of analogies, extreme cases, running explanatory models, and Gedanken experiments, and the implicit use of many expert imagery enhancement strategies. Our overall purpose is to refine concepts developed from expert protocols and to create new terminology for understanding implicit strategies at work in lesson structures. Case studies of corresponding classroom tapes provide initial exemplars indicating that when the strategies are suggested in a curriculum and presented in a way that maximizes their imagistic potential, students can use the expert thinking strategies as part of their learning process.

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Introduction

From expert think-aloud protocols, we have identified a number of strategies for evaluating, modifying, and enhancing explanatory mental models (Clement, 2002, 2003, 2006, to appear). In this paper, we attempt to identify exemplars of these strategies in several curricula. The strategies we have identified fall into three different categories or levels shown in Table 1.

Multiple-Level Set of Teaching Strategies
I. Fostering *Reasoning* Processes for Learning
II. *Case Selection* for Anchors, Bridges, Targets
III. *Tuning Cases* for Visualization

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Table 1. Levels of Teaching Strategies

Reasoning strategies can be considered student-learning strategies, and strategies such as learning by analogy or using Gedanken experiments are central to model based learning. However, the selection of cases to use for the analogy or the Gedanken experiment becomes very important, and this is another level of strategies. Once a basic case has been selected, there is a third level, of fine-tuning the cases for enhanced visualization or mental simulation. The paper is organized around these three levels of strategies because of this apparent hierarchy.

Objectives and Theoretical Perspective

Clement (in preparation) has identified a network of thinking processes that allow experts to generate ideas divergently (brainstorming) and then to constrain these ideas in a rigorous evaluative process that is highly convergent. These processes are central to evaluating mental models and therefore are central to learning.

From expert think-aloud protocols, we have identified four types of expert reasoning strategies: running explanatory mental models, using analogies, using extreme cases, and using Evaluative Gedanken Experiments. We have also identified a list of strategies the experts appear to use in order to select test cases to reason with and to enhance the imagistic qualities of these cases (Clement, 2003). We have found these expert reasoning strategies, case selection strategies, and imagery enhancement strategies in use by students in science classrooms where they are being encouraged to generate, evaluate, and modify their mental models. It has also been possible, in some cases, to document conceptual change on the part of individual students in such classes (Stephens & Clement, 2006b). In this study, we attempt to use these new insights about classroom learning processes to analyze lesson plans from a science curriculum that was developed expressly to support explanatory mental model generation and evaluation. Our goal is to develop a set of principles that teachers and curriculum developers can readily use in order to support their students in reasoning with and modifying their own dynamic explanatory models.

For us, an analysis of the types of strategies encompassed in Table 1 will be needed in order to make it possible to develop a theory of conceptual change teaching strategies**.** Also, since we intend to revise the curriculum examined in this study, our present work will serve as formative background for revisions. In addition, as we began to examine curricula in light of this theory, we anticipated seeing new aspects of the theory. One new aspect is that the previous theory had no level for fine-tuning the visual characteristics of cases and models. The distinction between the levels shown in Table 1 is implicit in the different ways the levels are treated in this analysis. Imagery enhancement strategies can apply to any case, while case selection strategies are dependent on the purpose for which the case is intended, for instance.

Theoretical Framework

It has been argued that the ability to generate and evaluate mental models is a crucial aspect of science and science learning (Darden, 1991); moreover, it is argued that science textbooks are organized around such models (Giere, 1988). Research continues to indicate the importance of mental modeling in both experts and students (Gentner, 2002; Nersessian, 1995; Nunez-Oviedo, 2003), but **a concern is that students often need to be helped to assimilate their prior experience** (Smith, DiSessa, & Roschelle) **into scientifically accepted models** (Driver 1983).

One powerful way to do this appears to be to run a Gedanken experiment (Gooding, 1992; Nersessian, 1993). Previous philosophical analyses include the structure of Gedanken experiments (Brown, 1986) and their function in scientific thinking (Kuhn, 1977; Sorensen, 1992). More recently, Gedanken experiments that were spontaneously generated and used by experts during problem solving have been investigated (Clement, 2002, 2006). In addition to their usefulness to experts, Gedankens appear capable of playing an important role in teaching and learning (Clement & Steinberg, 2002; Gilbert & Reiner, 2000). Some students can and will use Gedanken experiments to find solutions to problems when the problems are formulated in a way to encourage this (Reiner & Gilbert, 2000).

A case has been made for the value of divergent, qualitative methods in science thinking (Gooding, 1996). As well as Gedanken experiments, these methods include the use of analogies and limiting or extreme cases (Nersessian, 1992). It has been suggested that people use analogies to help construct mental models (Collins & Gentner, 1987; Gentner & Gentner, 1983) and that carefully constructed analogies can be used to address students' preconceptions in physics (Clement, 1993). These analogies can work by making use of "anchoring" conceptions that ground instruction on students' intuitions (Clement, Brown & Zietsman, 1989). Recent work shows that analogies can enable students to generate inferences (Podolefsky & Finkelstein, 2006). In addition to teacher-constructed analogies, student-generated analogies can also be used as a tool for understanding (Wong, 1993; Zietsman & Clement, 1990). Although textbooks have been analyzed for analogies (Harrison, 1994) and there has been research on students' use of analogy (Gentner & Toupin, 1986) and ability to run explanatory mental models (Clement & Steinberg, 2002), the focus has generally been on how analogies and explanatory models function rather than on how the cases they are based on are selected. Another non-formal reasoning process that has been documented in expert protocols is the use of extreme cases (Clement, to appear); these cases can also play a role in instruction (Zietsman & Clement, 1997).

There has been research on the role of imagery in physics problem-solving in experts (Nersessian, 1993) and students (Kozhnevnikov, Hegarty & Mayer, 2002; Reiner & Gilbert, 2000). It has been hypothesized that a mechanism involved in subjects' evaluation of their mental models is the use of mental animation to run the models (Hegarty, 1992). The use of mental animation has been investigated in problem solving by experts (Clement, 2006) and students (Hegarty, 1992; Clement, Zietsman & Monaghan, 2005). Some of the mental imagery involved appears to be kinesthetic in nature, as when expert physicists imagine exerting a push or a pull (Clement, 2006; Gooding, 1992). Kinesthetic imagery appears to be associated with physical intuition (Clement, 1994) and has been used in instruction (Camp, et al., 1994; Clement & Steinberg, 2002). Kinesthetic thinking appears to have an effect in problem solving in domains other than the physical sciences, as in geometry (Sellares & Toussaint, 2003), which suggests that the role of this form of thinking may be more fundamental than previously thought.

There has been little analysis of the various roles that expert processes and imagery play in supporting model construction in the classroom. Modeling theory is beginning to be reflected in innovative science curricula. Examples of curricula that have been developed to promote mental modeling are *CASTLE* (Steinberg & Wainwright, 1993), which uses air pressure as analogous to voltage differences in electric circuits; *Preconceptions in Mechanics* (Camp, Clement, et al., 1994), which is particularly designed to address student preconceptions; the *Model-based Analysis and Reasoning in Science* project (Raghavan & Glaser, 1995), a model-centered, computer-supported science curriculum for middle-school students; physics curricula that have grown out of the *Modeling Workshop Project* at Arizona State University (Wells, Hestenes, & Swackhamer, 1995); *Minds on Physics* (Leonard, Dufresne, Gerace, & Mestre, 1999); and *Energy in the Human Body* (Rea-Ramirez, Nunez-Oviedo, Clement, & Else, 2004), which promotes student development of dynamic mental models of respiration. Although there is initial research on students' spontaneous use of expert processes and imagery strategies in classrooms using some of the above curricula (Stephens & Clement, 2006a, b), until now, the curricula themselves have not been examined for their use of these strategies. Beyond this, we wish to integrate our prior work on imagery with our work on conceptual change toward building an expanded, more adequate theory of conceptual change that can underlie both the development and revision of curricula and their eventual implementation by teachers.

Design and Procedure

We investigate the usability of the list of expert reasoning and imagery enhancement strategies by analyzing a curriculum that our group was involved in developing (Camp, Clement, et al., 1994). Prior evidence exists from comparisons of gain scores that the experimental curriculum was more effective than traditional ones (Clement, 1993). Some of the strategies used in these lesson plans were conscious and explicitly described for the teacher, but others were used implicitly, as "interesting" things to do, with no explicit rationale.

Level I: Fostering Reasoning processes as Learning strategies

We began by identifying instances where the lessons were designed to invite students to run their explanatory models, to reason by analogy, to reason by extreme case, or to run Evaluative Gedanken experiments. (While analogies and extreme cases are well known as strategies, we think the other reasoning strategies have been poorly understood and poorly articulated.) We found that our definitions, originally formulated in terms of observables so that we could detect when these processes had been *used*, now needed to be refined so that we could detect when the processes had been *suggested* or *encouraged* as learning strategies. We identified places in the curriculum that were consistent with the following:

Analogies

We will consider that an **Analogy** has been proposed when, in order to facilitate reasoning about a situation A (the target), a situation B (the base) is suggested, which differs in some significant way from A, and an implicit or explicit suggestion is given to apply findings from B to A.

Extreme Case

We will consider that an **Extreme Case** has been proposed when, in order to facilitate reasoning about a situation A (the target), a situation E (the extreme case) is suggested, in which some variable from situation A has been maximized or minimized.

Explanatory Model

We will consider that **Running an Explanatory Model** has been encouraged when questions about a case concern some initially hidden feature that offers an explanation for why the system behaves the way it does—and when students are not likely to be able to cite answers from authority.

Evaluative Gedanken Experiments

We will consider that an evaluative Gedanken experiment has been proposed when the curriculum proposes an untested,* observable system designed to help evaluate a scientific concept, model, or theory—and gives the implicit or explicit suggestion for the students to predict aspects of the behavior of the system.

> *The system need not be untested by the person who proposes the experiment, but must be untested by the person who runs it. In other words, it must be improbable that the students would have had direct experience with the aspect of the system being tested or that they would know about it from authority.

As an exemplar, we will discuss a short section of a single lesson that we believe encourages the students to employ all four of the processes listed above as learning strategies.

Level II: Strategies for choosing cases for Anchors, Targets, and Bridging Analogies

The model-based curriculum that we are investigating uses analogies in a special way. Each lesson has a target concept, chosen to address a particular misconception that is known to be prevalent among high school science students (for instance, the misconception that a rigid object cannot push up against another object resting on top of it). For each target concept, there is an *explanatory model* (the slight compressibility, or springy-like quality, of even the most rigid matter) and a *target case*, chosen as a concrete exemplar of the concept (a book resting on a table).

To help students develop or retrieve the knowledge they need to understand the concept, an *anchor* is chosen that has an analogical relationship with the target, though this relationship is often initially not apparent to the students (such as a hand pushing on a spring). A good anchoring case needs to be something students can imagine well enough that they can “run” it in a mental simulation, in order to predict what will happen next (the spring will push back when compressed). It should be a case where students’ physical intuition (prior knowledge from perceptual motor schemas, Clement, 2003) will tend to lead them to make a confident and accurate prediction for the system.

Since the analogical relationship between the anchoring case and the target may be difficult for students to see—or even to accept from authority—the curriculum employs *bridging analogies* to bridge the gap between the two cases. These analogies are designed to allow the perceptual memories that students have in connection with the anchor (such as the feel of the push of a compressed spring against the hand) to be adaptively transferred via analogy. In the lesson to be analyzed below, the domain of application of the “springiness” schema is expanded from materials that are usually thought of as springy until it can apply to all matter. This idea is represented in Fig. 1, where B1-3 represents a sequence of bridging cases. The ~ is meant to indicate the fact that, at any point, a student may not “buy” the analogical relationship, or may encounter a conflicting schema (associated with a misconception) that make it difficult to bridge to the next case.

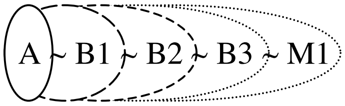


Figure 1. Bridging analogies: Expanding the domain of application of a schema

Clement (to appear) has described strategies that experts use to choose anchoring cases for themselves when reasoning about difficult problems. When applying our descriptions to the curriculum, we found that, with some modifications, these descriptions could also apply to strategies for choosing cases for the bridging analogies, and even for designing the explanatory models to be used as targets (such as the “springiness” model that is used to explain the existence of normal forces). These strategies reside at the middle level of our Multi-Level Set of Teaching Strategies (Table 1).

We are still in the process of honing and adding to our descriptions. For purposes of the present paper, we will use the descriptions below. In these descriptions, the *variables of interest* are the *sought* variables plus the *familiar* variables that interact with them. For instance, in the case of the rigid object that pushes, the sought variables are the normal force and the imperceptible deformation that produces it, while familiar variables are the force of gravity and the movement it produces.

Strategies for Choosing Anchoring Cases for Mental Simulation (that can yield predictions):

A1. *(Conviction)* Find a case where most students are intuitively confident of the relationship between the **variables of interest** (whether they are correct or not).

A2. *(Accuracy)* Find a case where students’ predictions concerning the variables of interest are likely to **agree with accepted physical theory**.

Strategies for Choosing a Target Case To Expose a Misconception:

T1. *(Exposing inaccuracy)* Find a case where students' predictions concerning the variables of interest are likely to **manifest known student misconceptions.**

T2: Avoid target cases that embody multiple misconceptions that have not been dealt with previously (try to do one at a time).

Strategies for Choosing Cases to Bridge Between the Anchor and the Target or to Extrapolate Beyond the Target:

B1. Choose a series of cases, beginning with one similar to the anchor, where each case increasingly shares features with the target.

B2. For each case, find one to which students can transfer, by analogy with the previously confident case, intuitive knowledge concerning the variables of interest.

Strategies for Designing Explanatory Models:

E1. Assemble initial versions of the model from prior schemas that are runnable, such as schemas activated by anchoring cases (e.g. the hand on the spring).

E2. Design a model that can be modified later to refine it toward the expert model.

Table 2. Level II: Strategies for choosing cases

Level III: Imagery Enhancement Strategies

In order to fine-tune the Anchoring, Bridging, or Target Cases so that they can be more easily visualized and/or run as a mental simulation, another group of strategies appears to be used. This is a group of *imagery strategies*, at the lowest level in our Set of Teaching Strategies. We believe this group is new, and it is here, for the first time, applied to the analysis of a curriculum. In the next section, a segment of curriculum will be coded for these strategies, and specific examples of each will be discussed. Any of these strategies may be applied to any of the cases above.

Strategies for Choosing or Improving Cases or Models via Imagery Enhancement (to enhance spatial reasoning or schema application for any of the above categories A, T, B, or E.)

I1. *(Important for most imagistic simulations)* Use a case that is as **simple and schematic** as possible (so that it is easy to visualize or to imagine kinesthetically).

I2. *(Important when manipulating variables in imagistic simulation)* Imagine a case whose particular features (such as **size and orientation**) are such that the experimental variables would be **easy to see** or observe or could be **manipulated with one's hands** if it were a real object.

I3. *(Important when imagery is difficult to perceive)* Imagine a case where aspects of the imagery that represent variables of interest are made more **extreme**.

I4. *(Important when imagery is especially difficult)* Use "**markers**" (mental diagrammatic notation that makes variable differences easy to imagine).

Table 3. Level III: Strategies for Imagery Enhancement

We seek to analyze a lesson, find strategies that were implicit before, and make them explicit. The purpose of the analysis is not to compare curricula or any particular set of features but to see whether new descriptors of learning strategies provide insights into the structure of these lessons. An important purpose is to help us refine our teaching strategy descriptions. A long-term goal is to develop new tools for understanding the structure of science lessons.

The Curriculum

All of the discussion to follow will draw on the three sequences below. They are presented here in the order in which they appear in the book.

I. Bridging Sequence from Normal Force.

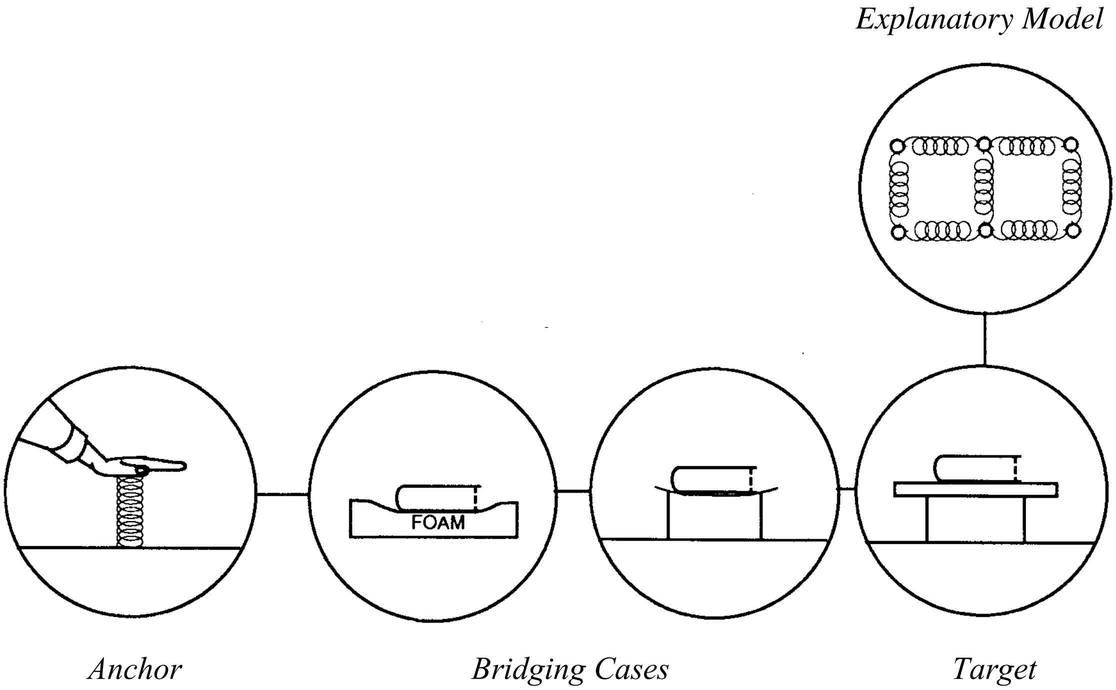
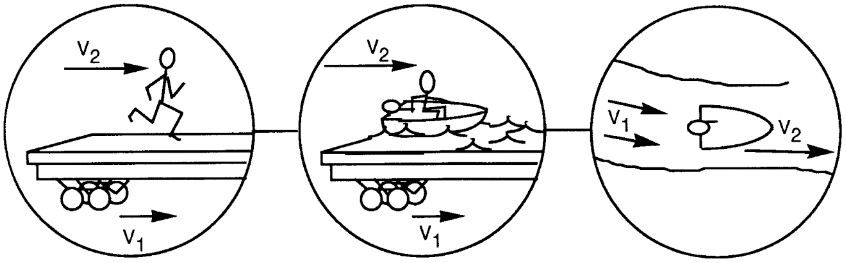


Figure 2. Bridging Sequence from Normal Forces Lesson

Students have trouble believing that a rigid inanimate object can exert a force. However, most students, when asked to imagine compressing a spring with their hand, will report that they believe the spring exerts a force back on their hand. The sequence above builds a bridge between the two cases. After considering the anchor, many students appear able to project the idea of springiness into the foam and say they think the foam will push up. The next case is a table so thin that it bends. This can be a controversial case, with some students believing it will and some that it won't exert a force. The explanatory model takes the "springiness" schema and assembles it into a configuration that can serve as an initial model of the bonds that hold "rigid" matter together.

II. Bridging Sequence from Relative Motion

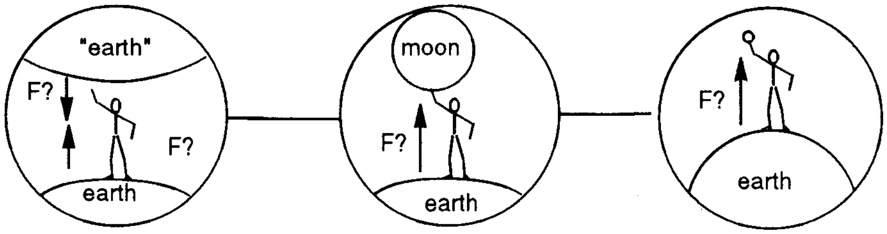


Anchor *Bridging Case* *Target*

Figure 3. Bridging Sequence from Relative Motion

Many students have trouble with problems in relative motion. It appears particularly difficult for students to imagine speed of an airplane with respect to the surrounding air, or speed of a boat with respect to the surrounding water. Day 1 of this unit encourages students to build imagery of the anchoring case, that of a student running on the flatcar of a train. Many students who are able to reason correctly with this case still have trouble on Day 2 with the velocity of a boat relative to the *current*. They tend to consider only how hard the engine is working when computing boat speed relative to the shore. A novel bridging case appears to help. In this case, students are asked to imagine a swimming pool on top of the flatcar. A boat powers around in the pool. Imagining the flatcar moving the water, rather than the current moving it, appears to provide concrete imagery that helps the students combine the velocities of the boat and the flatcar correctly. The task then is to create an analogy between the swimming pool on top of the flatcar with the current in the river. Many students still have trouble; imagery enhancement strategies applied to the Bridge and to the Target seem to help.

III. Bridging Sequence from Gravity



Anchor *Bridging Case* *Target*

Figure 4. Bridging Sequence from Gravity

The above is the theoretical structure of the learning pathway on Day 2 of the Gravity Unit. However, in the lesson plan itself, the cases are presented in a different order. First, students are invited to consider a number of scenarios involving small objects with the hope that their schemas and preconceptions considering the relation of small objects to gravity will be activated. This is important, because daily experience can lead to powerful misconceptions about gravity. After the scenarios with small objects, the target case of a tennis ball falling to Earth is presented. Many students do not believe that the tennis ball can exert a force on the Earth, believing that gravity is a property of large objects only (and perhaps planets only). The anchor is presented soon after the target. It activates a different set of schemas for most students, and they must try to reconcile conflicting mental imagery: the object, when considered as the "faller," may trigger a different set of schemas (and mental imagery) than when that same object is considered as the planet causing the fall.

Results: Examples of Coding

Level I. Reasoning processes/Learning strategies

We discuss the pedagogical roles of analogies, extreme cases, running explanatory models, and Gedanken experiments within the context of a single case.

Atlas drops one Earth onto another

The Anchor case in the Gravity lesson is used as an exemplar because it encourages the use of multiple learning strategies: the running of an explanatory model, the use of extreme case reasoning, and the running of a Gedanken experiment. Later in the lesson, this same case is incorporated into an analogy.

1. Students are encouraged to run a mental simulation of the effects of gravity in a new situation. This case was designed to help students **evaluate their explanatory model of gravity** by determining whether it can lead to a reasonable prediction in this situation.
2. It invites students to run an **Extreme Case** version of the target problem, where the object being dropped is the same size as the planet it is being dropped on.
3. It invites students to run a **Gedanken**. Because students have never tested this situation, it can be run as a Gedanken experiment, where their predictions from earlier, less extreme cases can be tested against their intuition that the effects in this case must be symmetric.
4. This case later plays a role in an **Analogy**: when students are invited to consider the Earth/Moon system, it is anticipated that they will see this as analogous to the Earth/Earth system.

Not every case will lead to this kind of sophisticated reasoning. To construct a learning pathway such as the above, which has the power to trigger animated discussions such as those that have been observed during administration of this lesson, cases must be chosen carefully. Fortunately, there are strategies for doing so.

Level II. Strategies for choosing Anchors; Criteria for Bridges, Target Cases, and Target Models

For two sequences from the curriculum, we consider the thinking that appeared to go into the selection of the anchors and the characteristics shared by the bridges, target Cases, and target Models.

Relative motion day 2

Table 4 below describes the characteristics of the cases in the flatbed-river current sequence and how they fit the criteria described in Table 2. Figure 5 is another view of the bridging case.

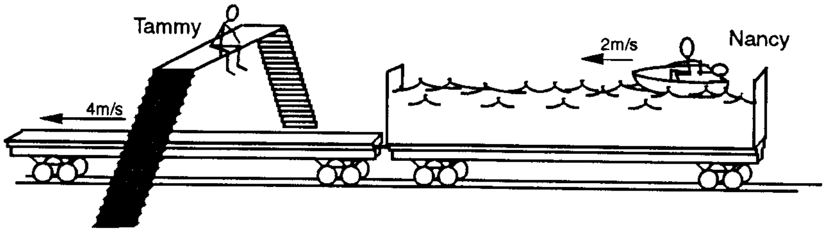


Figure 5: Pool on a Flatcar

Learning pathway	*Comments*
Anchor problem: person running toward the front of a moving flatcar	A1. Most students can confidently predict that the velocities will add. Having a human as one of the moving objects in this relative motion scenario may help students to imagine switching viewpoints between the mover and the observer on the ground. A2. Students' prediction that the velocities will add agrees with the principles of relative motion.
Target case: relative motion on a river	T1. Students have trouble taking the velocity of the water into account. Many will fail to add the velocity of the river to the velocity due to the boat engine. T2. This case targets the misconception about absolute motion only as it applied to motion due to a current.
Bridging case: swimming pool on top of a moving flat car. Velocity of a boat in the pool (velocity relative to the flatcar) and velocity of the flatcar (relative to the ground) add.	B2. This case is an innovative bridge between the flatcar and the river cases, where the movement of the water relative to the ground is due to the motion of the train rather than due to a current. Considering the boat moving through the pool on the flatcar as analogous to the person running on the flatcar appears to enable many students to transfer to this new case the knowledge they were able to tap into in order to reason correctly about the anchoring case,

Table 4. Unit #2 Relative Motion Day #2

Book on table:

The following sequence is formed around a series of bridging analogies (see Fig. 2 above).

Learning pathway	*Comments*
Target problem: book on table	T1. Students are likely to make confident predictions that manifest the common student misconception that rigid inanimate objects cannot exert a force. T2. Students are likely to believe, correctly, that there is a force on the table as a result of the pull of gravity on the book; the only misconception likely to be manifested here concerns the upward force exerted by the table on the book.
Anchor: hand compressing a spring	A1. Most students can retrieve kinesthetic imagery that convinces them that the spring will push back against their hand. A2. This prediction, that the spring will exert a force, is consistent with accepted physical theory.
Bridging case: Book resting on foam rubber	B1. This is the first of a series of cases that bridge between the anchor and the target. B2. Most students should be able to transfer their intuitive knowledge (or kinesthetic mental imagery) of the push of a spring against their hand to the push of foam against a book.
Bridging case: Thin, Bendy Table	B1. The bendy table shares more features with a rigid table than does a piece of foam rubber. B2. Some students should be able to make an analogy with the hand/spring case, in order to imagine the bendy table exerting a push. For others, the bendy table may activate their "rigid objects can't push" conception. This case has proven capable of stimulating active discussion among students.
Target Explanatory model	E1. Once students have activated a perceptual motor schema of "pushing back" through consideration of the hand-on-spring example, this schema can be assembled into an initial model of the bonds that hold "rigid" matter together. It is represented as a simple, schematic configuration of springs. E2. Later, by substituting "spring-like bonds" for the schematic image of springs, this model can be refined toward the expert model: elastic bonds between the molecules of rigid solids.

Table 5. Unit #1 Normal Forces – Day 1

We have evidence from classroom videotapes that students were able to reason with these cases, running mental simulations and engaging in all four types of reasoning processes from Level 1 during an implementation of this lesson plan (Stephens & Clement, 2006c).

Level III. Imagery enhancement strategies

Each of the cases described in the previous two sections has had imagery characteristics that made it amenable to visualizing and/or mentally manipulating. Our previous work (Stephens & Clement, 2006c) suggests that such mental imagery can be centrally important in student reasoning. We have observed experts using strategies to enhance the imagistic qualities of their cases (Clement, 2006, to appear) and students doing the same

(Stephens & Clement, 2006a). To see whether these strategies might apply to the pedagogical cases in the curriculum, we coded all the cases in several of the lesson plans; this helped us refine our categories. For the present purpose, two cases will be sufficient to illustrate how the four imagery enhancement strategies can apply to these pedagogical cases.

Bridge over river with swimming pool marker

Most students find it difficult or impossible to visualize the target case in Figure 3 well enough to be able to reason correctly about the effect of the current on the boat. Figure 6 is another view of this same target case, with the addition of a mental marker to make the variable of interest (the effect of the current) easier to visualize. Table 6 contains our imagery strategy coding for this enhanced case.

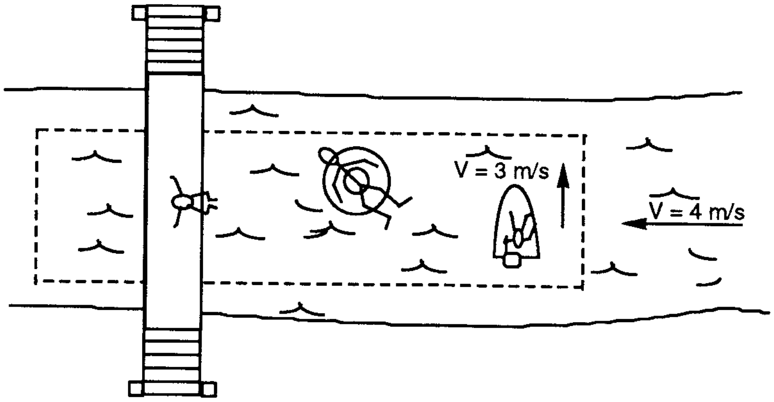


Figure 6: Relative motion target case with mental marker

Learning pathway	*Comments*
Target case: Boat in a river that has a bridge over it and an invisible box in it.	I4. This case, when initially presented, was designed to reveal the presence of a common student misconception about motion in a current. At this point, it is reintroduced with a new imagery strategy. Students are invited to imagine a box surrounding a section of water in the river, in order to imagine this section in analogy to the pool on the flatcar. Teachers report that this imaginary box improves students' ability to visualize the resulting motion of anything moving within the box. This box is a mental diagrammatic notation that makes the effects of motion due to current easier for students to see—and to combine correctly with effects of motion due to a motor. I2. In addition, in a previous, analogical case, students were invited to imagine standing on the bridge and reaching their hand down to feel the water going past.

Table 6. Unit #2 Relative Motion Day #2

Note that this case sacrifices some of the simplicity of earlier cases in order to employ markers. We hypothesize that imagining an (invisible!) box floating down the river with the current helped the students to "see" the current in a way that let them take its motion into account when running their mental simulations of the movement of the boat. The person on the inner tube probably also helped define the motion of the current, but did not seem to be sufficient without the box. In addition, imagining feeling the water going past their hands may have contributed kinesthetic imagery that was helpful to some students.

Atlas dropping tennis ball from a mile

The final case we will consider illustrates the use of an imagery enhancement strategy that, at first, sounds very similar to one of the learning strategies on the first level. The Level 1 strategy emphasized *changing a case into a new case* by maximizing or minimizing the *variable* that was under investigation in order to evaluate the effects of the variable. The new, Level III strategy, on the other hand, involves *fine-tuning a case* by making aspects of the *imagery* more extreme. The intent is to make the case easier to visualize. The coding should make this clearer.

Learning pathway	*Comments*
Target case: a tennis ball dropped from one mile high; will it exert a force on the Earth as it falls?	I1. The case is simple and schematic. I3. Earlier, students were asked why a ball falls when dropped. Although this case exaggerates a variable of interest (distance), it is not this variable that is being evaluated. We believe that the potential power of this case comes, rather, from the fact that its imagery is more extreme than the case of someone dropping a ball onto the floor.

Table 7. Unit #5 Gravity Day #2

The imagistic qualities of most of the cases examined appear to be consistent with multiple imagery enhancement strategies. For instance, the Earth/Earth case suggests a new strategy of symmetry enhancement as a way to add confidence to a prediction from a simulation.

Discussion

We plan to continue refining and expanding the set of teaching/ learning strategies. As we become more articulate about them, we believe they could prove quite valuable for science teachers, as they already appear to be for the experts who inspired them, the students for whom we refined them, and the curriculum sequences analyzed here.

Qualitative observations from video tapes of classes that used this curriculum (Brown and Clement, 1991; Clement, 1993) indicate that: (1) students appear readily to understand the anchoring cases; (2) however, many students indeed do not initially believe that the anchor and the target cases are analogous; (3) some of the bridging cases sparked an unusual amount of argument and constructive thinking in class discussions; in the normal forces lesson the flexible board case usually promoted the greatest discussion, and a number of students switched to the physicist's view at this point; (4) the lessons led many students to change their minds about or degree of belief in the physicist's view; (5) some students changed their minds toward that view during each major section of the lesson, e.g., after the anchor, bridge, model, and demonstration sections, leading us to hypothesize that each technique was helpful to some subset of students (Brown [1987] reports evidence from tutoring studies which provides further support for this hypothesis); and (6) students were observed generating several types of interesting arguments during discussion, such as: generation of analogies and extreme cases of their own; explanations via a microscopic model; giving a concrete example of a principle; arguments by contradiction from lack of a causal effect; generation of new scientific questions related to the lesson; and even spontaneous generation of bridging analogies. The set of observations in (6) gives us some reason to believe that, even though the lessons were designed primarily with content understanding goals in mind, some process goals were also being achieved as an important outcome.

The prior knowledge paradox

Their use of anchors means that the experimental lessons attempted to ground the student's understanding on prior knowledge (physical intuition in this case). Here one is faced with the paradox of prior knowledge and alternative conceptions: in order for difficult conceptual material to make sense to the student, it is important to connect somehow with the student's existing knowledge; but the student's existing intuition in the area is in conflict with the theory being taught. A way around this paradox was found by using anchoring examples. This method relies on the fact that students are globally inconsistent from a physicist's point of view; the student can simultaneously harbor in permanent memory an anchoring intuition and an alternative conception that are diametrically opposed in that view. When such conflicts motivate good discussions, *alternative conceptions may actually be used to advantage* in one sense. Such topics may have more "news value" to students—there is something unusual to be learned.

We will summarize our findings according to the three major strategy levels outlined in Table 1.

I. Fostering Reasoning Processes for Learning

In our coding, we found lesson plans that had both explicit and implicit suggestions for promoting the use of the expert reasoning processes.

We expected to find some evidence for this, but were surprised with the number and density of expert reasoning processes. For example, a single gravity lesson presented extreme cases, suggested analogies, invited students to run a Gedanken experiment, and had a number of points where students were asked questions designed to elicit and encourage them to run their explanatory models. The expert work helped us make clear distinctions between Gedanken experiments, analogies, extreme cases, and running an explanatory model, and we are now able to apply these distinctions to curriculum analysis.

II. Case Selection for Anchors, Bridges, Targets

We found ample use of these strategies in lessons such as the Book on the Table lesson. This study has also helped us to expand our lists of strategies for case selection and case refinement.

III. Tuning Cases for Visualization

Furthermore, the test cases in this lesson were consistent with a number of the strategies for imagery enhancement.

Something that has intrigued us in pilot work is the fact that, in classrooms using this curriculum, we have observed a wide variety of students adopting these strategies, including at times when the strategies have been presented only implicitly by the teacher. We have observed: 1) students contributing cases that were not in the lesson; 2) students introducing some of the planned cases before the teacher had a chance to; 3) students engaging in extended discussions of this material, some of which lasted as long as 45 minutes. We plan to pursue the documentation of such phenomena on a broader scale.

Conclusions

The overall purpose of this study was to refine concepts and create new terminology for understanding implicit strategies at work in lesson structures. We are using these case studies to help us get the teaching strategy descriptions right. We would like to cast these strategies in a form that will optimize their usefulness for teachers and curriculum developers. Our case studies of corresponding classroom tapes provide initial exemplars indicating that when these strategies are suggested in a curriculum and presented in a way that maximizes their imagistic potential, students can use these expert thinking strategies as part of their learning process.

We feel that some of the findings of this study are underrepresented in the literature. Specifically, we believe the following are contributions: applying the imagery enhancement strategies to the analysis of curricula; proposing the idea that analogies involve mental simulations and a transfer of imagery or physical intuition from one case to another; being able to articulate observable criteria for differentiating the following four processes from each other: thought experiments (including Gedanken experiments), extreme cases, analogies, and running explanatory models. We have documented these teaching and imagery enhancement strategies in a curriculum. We have observed experienced teachers using many of the strategies, and have observed spontaneous use of many of them by students. If we can become articulate about these strategies, they should be quite valuable for science teachers.

References

Brown, J. R. (1986). *International Studies in the Philosophy of Science: The Dubrovnik Papers*, p.1.

Brown, D., & Clement, J. (1991). Classroom teaching experiments in mechanics. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), Research in physics learning - theoretical issues and empirical studies. San Diego, CA: San Diego State University.

Camp, C., Clement, J., Brown, D., Gonzalez, K., Kudukey, J. Minstrell, J., Schultz, K., Steinberg, M., Veneman, V., and Zietsman, A. (1994). Preconceptions in mechanics: Lessons dealing with conceptual difficulties. Dubuque, Iowa: Kendall Hunt.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30* (10), 1241-1257.

Clement, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. Tirosh, D. (Eds.), Implicit and explicit knowledge. Norwood, NJ: Ablex Publishing Corp.

Clement, J. (2002). Protocol evidence on thought experiments used by experts. In Wayne Gray and Christian Schunn (Eds.), Proceedings of the Twenty-Fourth Annual Conference of the Cognitive Science Society 22, 32. Mahwah, NJ: Erlbaum.

Clement, J. (2003). Imagistic Simulation in Scientific Model Construction. In R. Alterman and D. Kirsh (Eds.), *Proceedings of the Twenty-Fifth Annual Conference of the Cognitive Science Society, 25*. Mahwah, NJ: Erlbaum, 2003, pp. 258-263.

Clement, J. (2006). Thought experiments and imagery in expert protocols. In L. Magnani (Ed.), *Model-Based Reasoning in Science and Engineering*. London: King's College Publications.

Clement, J. (to appear). *Creative Model Construction in Scientists and Students: The Role of Analogy, Imagery, and Mental Simulation.*

Clement, J., Brown, D. & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring' conceptions for grounding instruction on students' intuitions. *International Journal of Science Education, 11*, 554.

Clement, J. & Steinberg, M. (2002). Step-wise evolution of models of electric circuits: A "learning-aloud" case study. *Journal of the Learning Sciences, 11*, 389-452.

Clement, J., Zietsman, A., & Monaghan, J. (2005). Imagery in science learning in students and experts. In J. Gilbert (Ed.), *Visualization in Science Education*. Dordrecht, The Netherlands: Springer.

Collins, A., & Gentner, D. (1987). How people construct mental models. In D. Holland & N. Quinn (Eds.), *Cultural Models in Thought and Language*, p. 243. Cambridge, UK: Cambridge University Press.

Darden, L. (1991). *Theory change in science: Strategies from Mendelian genetics*. New York: Oxford.

Driver, R. (1983) The fallacy of induction in science teaching. *The Pupil as Scientist?* Chapt. 1. Milton Keynes: Open University Press. pp. 1-10.

Gentner, D. (2002). Psychology of mental models, in N. J. Smelser & P. B. Bates (Eds.), *International Encyclopedia of the Social and Behavioral Sciences*, p. 9683. Amsterdam: Elsevier Science.

Gentner, D., & Gentner, D. R. (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A. L. Stevens (Eds.), *Mental Models*, p. 99. Hillside, NJ: Erlbaum.

Giere, R. N. (1988). *Explaining science: A cognitive approach.* Chicago: Chicago University Press.

Gilbert, J. K., & Reiner, M. (2000). Thought experiments in science education: Potential and current realization. *International Journal of Science Education, 22*(3), 265-283.

Glynn, S. M. (1991). Explaining Science Concepts: A Teaching-with-Analogies model. In S. M. Glynn, R. H. Yeay, & B. K. Britton (Eds.), The Psychology of Learning Science (pp. 219-240). Hillsdale, NJ: Erlbaum.

Gooding, D. (1992). What is experimental about thought experiments? In D. Hull, M. Forbes & K. Okruhlick (Eds.), *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, 2: Symposia and Invited Papers*, (pp. 280-290). East Lansing, MI: Philosophy of Science Association.

Gooding, D. (1996). Creative rationality: Towards an abductive model of scientific change. *Philosophica, 58* (2), 73-102.

Harrison, A. G. (1994). Is there a scientific explanation for refraction of light? - A review of textbook analogies. Australian Science Teachers Journal. 40, 2, 30-35.

Hegarty, M. (1992). Mental animation: inferring motion from static displays of mechanical systems. *Journal of Experimental psychology: Learning, Memory, and Cognition, 18*(5), 1084-1102.

Kozhevnikov, M., Hegarty, M., Mayer, R. (1999). *Students' use of imagery in solving qualitative problems in kinematics*. Paper presented at the Annual Meeting of the American Educational Research Association, Montreal, Canada.

Kuhn, T. S. (1977). The function of thought experiments. In T. Kuhn (ed.) *The essential tension*. Chicago: University of Chicago Press.

Leonard, W. J., Dufresne, R. J., Gerace, W. J., & Mestre, J. P. (1999). *Minds on physics.* Dubuque, IA: Kendall/Hunt.

Nersessian, N. (1992). Constructing and instructing: The role of 'abstraction techniques' in creating and learning physics. In R. Duschl & R. Hamilton (Eds.) *Philosophy of science, cognitive psychology and educational theory and practice* (pp. 48-68). New York: State University of New York Press.

Nersessian, N. (1993). In the theoretician's laboratory: Thought experimenting as mental modeling. In Hull, Forbes, & Okruhlick (eds.), pp. 291-301.

Nersessian, N. (1995). Should physicists preach what they practice? Constructive modeling in doing and learning physics. *Science & Education*, 4(3), 203-226.

Nunez-Oviedo, M. C. (2003). Teacher-Student Co-Construction Processes in Biology: Strategies for Developing Mental Models in Large Group Discussions, unpublished doctoral dissertation, University of Massachusetts, Amherst, MA.

Podolefsky, N., & Finkelstein, N. (2006). Use of analogy in learning physics: The role of representations. *Phys. Rev. ST Phys. Ed. Res. 2*, 020101.

Raghavan, K., & Glaser, R. (1995). Model-Based Analysis and Reasoning in Science: The MARS Curriculum. Science Education, 79(1), 37-61.

Rea-Ramirez, M. A., Nunez-Oviedo, M. C., Clement, J., & Else, M. J. (2004). *Energy in the human body: A middle school life science curriculum.* Amherst: University of Massachusetts

Reiner, M. (1998). Thought experiments and collaborative learning in physics. *International Journal of Science Education, 20*, 1043-1058.

Reiner, M., & Gilbert, J. (2000). Epistemological resources for thought experimentation in science learning. *International Journal of Science Education, 22*(5), 489-506.

Sellares, J. A., & Toussaint, G. (2003). On the role of kinesthetic thinking in computational geometry. *International Journal of Mathematical Education in Science and Technology, 34*, 219.

Smith, J., diSessa, A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3*(2). 115-163.

Sorensen, R. (1992). *Thought Experiments.* Oxford: Oxford University Press.

Steinberg, M. S. and Wainwright, C. L. (1993). Using models to teach electricity – the CASTLE project. *The Physics Teacher*, Vol. 31, Sept. 1993, pp. 353-357.

Stephens, L., & Clement, J. (2006a). Running Effective Classroom Thought Experiments: What Expert Protocols and Imagery Indicators Can Tell Us. Paper presented at AERA 2006, San Francisco.

Stephens, L., & Clement, J. (2006b). Evidence for dynamic imagery during model construction in classroom discussions. Poster presented at AAPT 2006, Syracuse, New York.

Stephens, L., & Clement, J. (2006c). Depictive gestures as evidence for dynamic mental imagery in four types of student reasoning. In L. McCullough, L. Hsu, & P. Heron (Eds.). *2006 Physics Education Research Conference: AIP Conference Proceedings 883* (pp. 89-92). Melville, NY: American Institute of Physics.

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. *American Journal of Physics, 63*, 606.

Wong, E. D. (1993). Self-generated analogies as a tool for constructing and evaluating explanations of scientific phenomena. *Journal of Research in Science Teaching, 30*, 367.

Zietsman, A., & Clement, J. (1990). Using anchoring conceptions and analogies to teach about levers. 1990 Annual Meeting of the American Educational Research Association, Boston, MA.

Zietsman, A., & Clement, J. (1997). The role of extreme case reasoning in instruction for conceptual change. *Journal of the Learning Sciences, 6*, 61.