ANCHORING STUDENT REASONING IN PRIOR KNOWLEDGE: CHARACTERISTICS OF ANCHORING CASES IN A CURRICULUM[1]

We analyze strategies for selecting and honing Anchoring Cases, which are used to elicit useful—but often implicitly held—prior knowledge possessed by most students. In an innovative model-based high school mechanics curriculum, each unit presents a Target Case, designed to elicit a persistent misconception, and an Anchoring Case. These are connected by a set of Bridging Analogies that enable the students to transfer a conception from Anchor to Target in a series of gradual steps. The curriculum has produced significant gain differences over traditional instruction on measures of understanding. This suggests the usefulness of the pedagogical strategies; however, experience has shown that it is no easy matter to create successful Anchoring Cases. We analyzed these Anchoring Cases in terms of their consistency with previously identified expert design strategies and newly identified strategies. We have organized and honed the strategies into a coherent framework (part of a much larger framework presented in Clement, 2008a), designed to help with 1) predicting which Anchoring Cases are likely to be effective; 2) developing new Anchoring Cases; 3) forming an initial theory about how and why Anchors work. These findings have implications for lesson design, teaching strategies, and pedagogical theories of conceptual change.

A. Lynn Stephens, University of Massachusetts-Amherst
John J. Clement, University of Massachusetts-Amherst

Introduction

Bridging analogies are a powerful way to address student preconceptions (Clement, 1993). This pedagogical strategy works by beginning with a situation that taps into prior knowledge of the students and using it as the base of an analogy. This situation is called the Anchoring Case. A transfer of this prior knowledge to a less intuitive case, the Target Case, is fostered by introducing a series of intermediate analogue cases, beginning with one close to the anchor and continuing with cases that share more and more features with the target.

This strategy has been used in a successful model-based high school curriculum designed to deal with persistent misconceptions in mechanics (Camp, et al., 1994). However, it is no easy matter to create successful analogical sequences that tap into prior knowledge

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held by most students and that allow most students to transfer this knowledge successfully along the entire bridge and into the often counter-intuitive target case. The anchoring cases in this curriculum were developed at least partly by drawing on extensive experience in the classroom and on the intuitive knowledge of highly skilled and experienced teachers. Since this curriculum produced significant gain differences in pre-post measures of comprehension compared with traditional instruction (Brown, 1992; Clement, 1993), we are interested in understanding the characteristics of the cases that were used, particularly the anchoring cases. We would like to identify these characteristics so that we may develop an organized set of design principles with which to select and hone anchors for other difficult concepts in middle and high school science.

In another track of our work, case studies have revealed that experts can put considerable effort into selecting test cases for their own reasoning (Clement, 1989, 2008a). Through this analysis, we have identified a number of expert design principles. The anchoring cases in the mechanics curriculum appear to be consistent with many of these principles. Therefore, we began by analyzing the anchoring cases in the curriculum in terms of the previously identified expert design strategies and then continued, via open coding (Strauss and Corbin, 1997), to identify new strategies exemplified by the anchors in the curriculum. We then began organizing and honing the strategies into a coherent framework, which forms a small part of a much larger framework of model-based pedagogical strategies being investigated by our group.

Example of an Anchor

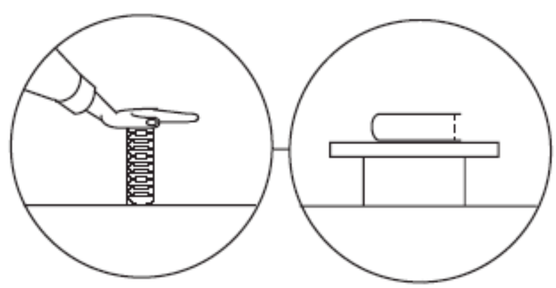

Figure 1. Anchoring Case of Hand-on-Spring in Analogy with Target Case of Book-on-Table

The following is a composite scenario drawn from actual experiences of team members in the classroom.

A student is confident that an inanimate object cannot exert a force. His invalid preconception persists across a wide variety of cases: he does not believe that a table exerts a normal force on a book resting upon it or that a wall exerts a normal force on a fist that smacks into it. However, when asked whether a stiff spring would exert an upward force on his hand if he were to hold it down in a compressed position, the student replies that it would. “The spring wants to be in a different position. It will push back against my hand trying to get back to where it wants to be.” When asked whether the hand/spring system is analogous to the book/table system, the student replies that they are not. However, the teacher believes that the beginnings of a mature concept of normal forces exist within the student's conception of the hand/spring system. Therefore, this system can be used as the *anchor* for the lessons that follow.

The definition we will use in this paper:

Anchor: *1. a widely held valid preconception; a knowledge structure that a) appears self-evident to many students, needing no explanation or support from authority to be believed, and b) is in rough agreement with accepted physical theory. Also referred to as an* anchoring conception.
2. a case that elicits the anchoring conception; a concrete exemplar. Also known as an anchoring example *or an* anchoring case.

When we use the term 'anchor' in this paper, we mean both the case and the conception it exemplifies. The idea that the spring pushes back is an anchoring conception for the above student. The hand/spring system can be used, for this student, as an anchoring case for the initially counter-intuitive concept of normal forces.

Although a single case can be an anchor for some students and not for others (i.e., it elicits the desired anchoring conception from only some students), in this paper we consider cases that have proven to be anchors for at least 70% of the students they were tested on. We will also discuss some cases that did not initially test as anchors for most students but were modified and have since been associated with large pre-post gains when used in the classroom.

Objectives and Theoretical Perspective

The pedagogical strategies to be discussed here are part of a much larger network of strategies under investigation by the team. Clement (2008b) describes a way of organizing this large and complex network into six levels of strategies considered at different time-scale levels. Examples of each level are described in the book *Model Based Learning and Instruction in Science,* edited by Clement and Ramirez (2008).

6-Curriculum Integration Strategies	2-6 months
5-Unit Sized Modeling Strategies	3-15 days
4-Lesson Strategies	10-80 Minutes
3-Single Model Element Strategies	.2-15 Minutes
2-Individual Cognitive Strategies for Teacher "Moves" in Discussion	5-100 seconds
1- Dialogical Tactics	1-20 seconds

A previous paper (Stephens and Clement, 2007) dealt with the strategies in Table 1, below. These strategies, such as "Propose an Analogy," were considered in terms of how teachers could use them as individual cognitive "moves" in classroom discussion, which is a Level 2 strategy in Clement's hierarchy. For instance, a teacher or student may spontaneously introduce an analogy into discussion in an attempt to make their ideas more accessible to others. Such an analogy may be considered only briefly, and, once its work is done, it may disappear from discussion. It is important to be clear, though, that many of these strategies can be used at different time scales. "Larger" bridging analogies, for instance, may be planned in advance by the teacher or curriculum developer and used as the focus of an entire lesson, forming a learning pathway that specifies intermediate models between the student preconceptions and the target model. In this case, the analogy becomes a Level 4 strategy. The anchor, target, and possibly bridges of the analogy may be tested and honed through years of teaching experience, or developed through the use of tutoring studies. At even longer time scales, a particular analogy has, at times, been chosen to be the "global analogy" for a unit or even an entire curriculum, used for several days or weeks and explored in depth. In this case, the use of analogy becomes a Level 5 or 6 strategy. Such a global analogy is the use of air pressure as analogous to voltage pressure in the CASTLE curriculum (Steinberg, et al., 1995; Clement and Steinberg, 2002).

To Foster Reasoning Processes for Learning

- Encourage students to Run their Explanatory Model.
- Propose an Extreme Case.
- **Propose an Analogy.**
- Propose a Gedanken Experiment.

To Select Cases

- **For Anchors**
  - **Choose a case where most students are intuitively confident of the relationship between the variables**
  - **Choose a case where students' predictions are likely to agree with accepted physical theory**
- For Bridges
  - Choose a series of cases where each increasingly shares features with the target.
  - For each case, find one to which students can transfer intuitive knowledge by analogy with previous case
- For Targets
  - Choose a case where students' predictions are likely to manifest known student misconceptions.
  - Avoid target cases that embody multiple misconceptions that have not been dealt with previously.
- For Explanatory Models
  - Assemble initial versions of the model from prior schemas that are runnable (e.g. the hand on the spring).
  - Design a model that can be modified later to refine it toward the expert model.

To Enhance Imagery by Tuning the Cases

- **Use a Case that is Simple and Schematic.**
- **Use a Case that would be Easy to See if it were real.**
- Use a Case where the Imagery is More Exaggerated.
- **Use "Markers."**

Table 1. Strategies for Anchors fall within a larger set of strategies (Stephens and Clement, 2007) (Strategies in bold-face are discussed in the present study.)

Here, we focus on strategies for selecting anchors for lesson-sized analogies; this use falls at Level 4. Thus, the cases analyzed herein, from a model-based curriculum, were each designed to anchor an entire lesson (Camp, et al., 1994).

Our objectives are:

1. Identify characteristics in common for anchoring cases that appear to have been successful in instruction;

2. Articulate these characteristics as a coherent set of design strategies;

3. Investigate the list of strategies by using it to code anchors and asking whether the strategies apply;

4. Investigate whether the list can make useful distinctions between cases that work as anchors and those that don't;

5. Uncover potential explanations for the fact that some anchors have proven less successful than others;

6. Ask whether the list could be used to suggest improvements to cases.

7. Push the development of theory by using key contrasting cases to generate grounded hypotheses for what makes anchors effective.

We do not attempt here to cover each strategy in depth; rather, our purpose is to introduce the strategies by giving an idea of how an organized list may be used.

Theoretical Framework

A case has been made for the value of divergent, qualitative methods in science thinking (Gooding, 1996); these methods include the use of analogies (Nersessian, 1992). It has been suggested that people use analogies to help construct mental models (Collins and Gentner, 1987; Gentner and Gentner, 1983) and that carefully constructed "bridging" analogies can be used to address students' preconceptions in physics (Clement, 1993). Recent work shows that analogies can enable students to generate inferences (Podolefsky and Finkelstein, 2006). In addition to teacher-constructed analogies, student-generated analogies can also be used as a tool for understanding (Wong, 1993; Zietsman and Clement, 1990). Some useful reviews of instructional analogies already exist (Dagher, 1994, 1995; Duit, 1991; Harrison, 1994), but the focus has generally been on how analogies and explanatory models function rather than on how the cases they are based on are selected.

A number of authors have measured learning gains associated with instruction that uses analogies, including Bulgren, et al. (2000), Glynn, et al. (2003), Mason (1994), Harrison and Treagust (1996), Venville and Treagust (1996), Dupin and Johsua (1989), Minstrell (1982), Brown (1992) Brown and Clement (1992), and Clement (1993). Glynn (1991) introduced a six step strategy he called "Teaching with Analogies (TWA)," an approach that includes steps for mapping similarities between the analogue and target explicitly, and for indicating where the analogy breaks down.

Others, however, have sounded caution on the limitations of using analogies (Yerrick, et al., 2003; Else and Clement, 2008). For example, Harrison and Treagust (1996), in a study of the effectiveness of analogies used in 8th to 10th grade classrooms, found some positive effects of analogies, but they also found that some students preferred less accurate models of atoms over others and that many students thought that atoms were alive and divide like cells. (See also Duit, et al., 2001).

Analogies can work by making use of "anchoring" conceptions and "anchoring" cases that ground instruction on students' intuitions (Clement, Brown and Zietsman, 1989), although these authors found that some "brittle" anchors were of surprisingly limited use in instruction. Clement, et al. (1989), diSessa (1988), and Hammer (1996), have called for the systematic study of students' positive preconceptions, or "anchors," to use as the base of an analogy. Clement, et al. (1989), found that different examples of what appear to experts to be the same physical principle varied strongly with respect to whether students could understand them as examples of the principle. This means that one has to be quite careful in choosing examples for the base of an analogy; i.e,. base examples need to be tested with students. This contrasts with a view of analogy as a simple short cut to understanding, and indicates that specialized efforts may be necessary for finding anchors. These considerations may eventually help us explain why previous studies have found mixed results in using analogies.

Design and Procedure

There is empirical evidence that anchoring cases work for experts as well as students (Clement, 1989, 2008a). In view of this, our objective is to identify characteristics in common for anchoring cases that appear to have been successful in instruction and to uncover potential explanations for the fact that some anchors have proven less successful than others. We began with a set of design strategies gleaned from analysis of expert protocols and suggested by curriculum authors, and coded anchoring cases from the curriculum for consistency with these strategies. We also coded similar cases that had been considered as candidates for the curriculum but had not tested well with students. We then used open coding to identify new characteristics held in common by the most successful anchoring cases (as identified by the differences in gains between classrooms using these lessons and classrooms using traditional curricula), and we looked for principles of design suggested by these characteristics. Archival videotapes of classrooms using the curriculum were used in this phase of the analysis to help us understand how the anchors were actually used by the teacher and students and to provide some insight into which characteristics were the most important. Finally, we organized and honed design strategies into a coherent set so that we could examine both the practical and theoretical implications.

In an early study (Clement, et al., 1989), a diagnostic test was given to students to identify anchors. A case was considered an anchor for a student if he or she made a correct response to the problem and indicated a confidence rating in the answer above a certain score. A case was considered a group anchor if the example was determined to be a confident anchor on the diagnostic test for about 70% of students in the sample. However, not all of these anchors proved useful in instruction. A curriculum in mechanics (Camp, et al., 1994) was designed around anchors that were incorporated into series of bridging analogies. Here, too, some anchors were determined to be more successful than others. At times, students may need to work with an anchoring case in order for it to be effective. A central anchoring conception was used successfully in this way in an innovative electricity curriculum (Steinberg, et al., 1995), where effort was made to strengthen and clarify the imagery elicited by the anchoring case.

Important insights were gained by comparing the characteristics of the early candidates for anchors found in the diagnostic with the characteristics of the anchors eventually used in the mechanics curriculum, especially those associated with high pre-post gain differences over controls. We will focus on two of these comparisons.

The set of design strategies for anchors that we use in the present study is given below.

Design Strategies for Anchoring Cases

A. Strategies for selecting cases for anchors:

1) (Validity) Find a case where students' predictions concerning the variables of interest are likely to agree with accepted physical theory.

2) (Conviction) Find a case where most students are intuitively confident of the relationship between the variables of interest.

3) (Imageability) Find a concrete case evoking imagery that has kinesthetic and/or visual components.

4) (Transferability) Find a case for which students are able to transfer their intuitive knowledge about it into the target case.

    a) Avoid "brittle" cases where a very small change in the case tends to cause a change in the intuition that is triggered for the students. E.g., avoid cases that rely on symmetry.

5) (Explanatory potential) Necessary for anchors used in learning pathways that lead to explanatory models. Find a case that:

    a) has a causal agent in it.

    b) has a causal agent in it that can be simulated kinesthetically—allowing the student to build on the natural causality of his or her muscular system

    c) allows the student to visualize causal aspects that are normally invisible in the target.

B. Strategies for selecting or improving (tuning) cases for anchors: increasing conviction, accuracy, or transferability through imagery enhancement

1) (Imagistic clarity) Find a case that does any or all of the following:

    a) is as simple and schematic as possible (is easy to visualize mentally; is spatially manipulable).

    b) can tap into intuitive kinesthetic or tactile knowledge that most students have developed through their everyday bodily interactions with the physical world (e.g., most students can imagine pushing against a springy solid and imagine feeling the resulting push back against their hand).

    c) uses "markers" (diagrammatic notation that makes variable differences easy to imagine or observe).

2) (Runnability) Find a case that:

    a) is easy to set in motion mentally (so that students find it easy to imagine the anchoring situation and to predict what will happen next).

    b) allows the student to transfer runnability from the anchor to the target, to see mentally the similarity between results of running the anchor case and running the target case .

Table 2. Set of Design Strategies for Anchoring Cases for Mental Simulation (Categories A and B correspond to the second and third categories in Table 1.)

If we apply the strategies in Table 2 to the Hand-on-Spring example of Figure 1, a case that has proven very successful as an anchor for the existence of normal forces, we obtain the results in Table 3.

UNIT 1: NORMAL FORCES **Day 1**	**Anchor: Push down with your hand on a bed spring. Does the spring push back?**
This unit produced large gain differences on pre-post: 54.5 percentage points, compared with 28.2 percentage points for controls.	Target: Book on Table (existence of normal forces)
A. CHOOSING CASES	
1) *(Validity)* **Find a case where students' predictions** concerning the variables of interest **are likely to agree with accepted physical theory**.	YES (93% on diagnostic)
2) *(Conviction)* **Find a case where most students are intuitively confident** of the relationship between the variables of interest.	YES (80% on diagnostic)
3) *(Imageability)* **Find a concrete case** evoking imagery that has kinesthetic and/or visual components.	YES
4) *(Transferability)* Find a case for which students are able to transfer their intuitive knowledge about it into the target case.	YES (tutoring interviews)
a) Avoid "brittle" cases where a very small change in the case tends to cause a change in the intuition that is triggered for the students. E.g., avoid cases that rely on symmetry.	YES
5) *(Explanatory potential*) Necessary for anchors used in learning pathways that lead to explanatory models. Find a case that:	
a) has a causal agent in it.	YES
b) has a causal agent in it that can be simulated kinesthetically—allowing the student to build on the natural causality of his or her muscular system.	YES
c) allows the student to visualize causal aspects that are normally invisible in the target.	YES
B. CHOOSING OR IMPROVING (TUNING) CASES: increasing conviction, accuracy, or transferability through imagery enhancement	
1) *(Imagistic clarity)* **Find a case that does any or all of the following:**	
a) is as simple and schematic as possible (is easy to visualize mentally; is spatially manipulable).	YES
b) can *tap into intuitive kinesthetic or tactile knowledge* that most students have developed through their everyday bodily interactions with the physical world (e.g., most students can imagine pushing against a springy solid and imagine feeling the resulting push back against their hand).	YES
c) uses "markers" (diagrammatic notation that makes variable differences easy to imagine or observe).	NO
2) *(Runnability)* **Find a case that:**	
a) is easy to run as a mental simulation (so that students find it easy to imagine the anchoring situation and to predict what will happen next).	YES
b) allows the student mentally to *see* the similarity between results of running the anchor case and running the target case.	NO (needs cases bridging to the target to succeed)

Table3. Hand-on-Spring Case Coded for Design Strategies

Note that the design of this case appears consistent with almost all of the strategies in the list. This motivates us to try using the strategies to analyze differences between some successful and unsuccessful anchors.

Comparison One

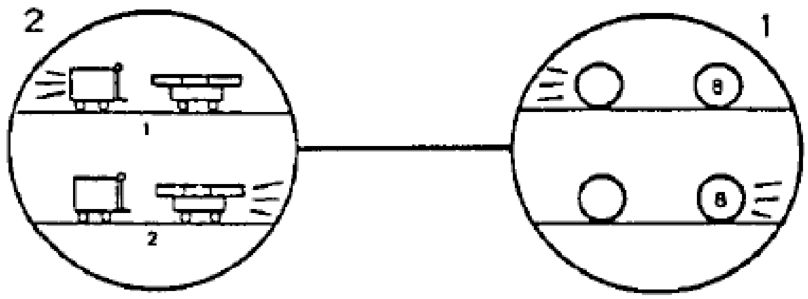

Figure 2. Analogy Diagram for Log Problem II and its Target.

Log Problem II

An insane criminal has captured a famous strongman and given him a choice:

> Situation 1: he can be on the moving boxcar in Figure 2 (at the top of the drawing on the left);
>
> Situation 2: he can be on the stationary boxcar (at the bottom of the drawing on the left).

In each situation, the other boxcar has a log on it. In either situation, his chest will meet the log head-on. Both cars are free to roll and both weigh one ton.

Our strongman's chest would:

- feel more force in Situation 1.
- feel more force in Situation 2.
- feel the same force in both situations.

The above problem was tested in a 1989 diagnostic test (Clement, et al., 1989). It was anticipated that most students would predict the strongman would feel the same force in the two situations. If so, this case could serve as an anchor for the target case of a moving object colliding with an identical stationary object. However, it was found that only about half of the students believed the forces would be the same and less than half were confident of this. (See Table 4a below.) Nonetheless, the investigators hoped that, when this case was used in mid-curriculum after other lessons and experiences with other topics, this percentage would rise enough to use it as an anchor. Unfortunately, in tutoring trials, it was found that even when a student strongly believed the forces would be equal in the two situations, he was unable to transfer this knowledge to the case of two identical inanimate objects colliding (Brown and Clement, 1989).

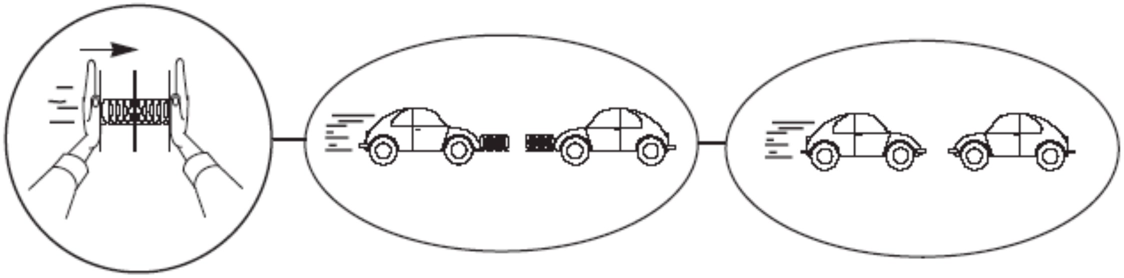

Figure 3. Analogy Diagram for Unit 9 Anchor, a Bridging Case, and the Target

Two Hands, Two Springs, and a Board

Two hands push on two springs with a board in between. (See the left-most drawing in Figure 3.) The hand on the left moves while the hand on the right stays still. On which hand is a greater force exerted?

Unlike the log problem, this case proved quite successful as an anchor. It was used on successive days in Unit 9: Newton's Third Law in the mechanics curriculum, a unit that produced large gain differences on pre/post-tests. Students averaged 26.0% correct answers on a pre-test compared with 70.2% correct on a post-test, for an average gain of 44.2 percentage points (Clement, 1993). A control group had average gains of only 14.5 percentage points.

Why was this case so successful? There are a number of similarities between it and the log case: both use forces applied to the human body and both involve a stationary and a moving situation. The list of design strategies can prove useful here, in helping us articulate differences that may not be immediately obvious (see Table 4a and b). One way to look at these differences is as a design problem. If we have a case that is not working as an anchor, a possibility is to improve it, either by adding or changing elements or by fine-tuning the imagistic qualities of the case.

One characteristic that the log problem does not have is a causal agent that can be visualized. Students appear to have an intuitive sense that a force should be associated with movement (Brown and Clement, 1989; Clement, 1993), and in the case of a spring, movement in response to a force is comparatively easy to imagine. In fact, if we add a spring to one of the boxcars, we have something similar to a focusing question used in the lesson (but not shown in Figure 3), where one cart is attached to a spring and another is not. In a problem on the diagnostic that had two identical carts with a spring attached to only one of them (Carts Problem II, Clement, et al., 1989), the results were low levels of accuracy and low levels of conviction (32% and 23% of respondents, respectively). If we add symmetry by making the passengers and contents equal and attaching the spring to both vehicles, we obtain the middle, bridging case shown in Figure 3. A similar symmetrical problem on the diagnostic had two identical carts with a spring compressed between them but attached to neither (Carts Problem I, Clement, et al., 1989). This produced high levels of accuracy and conviction (96% and 83% of respondents, respectively)—but relies on symmetry and is a brittle case that does not transfer well. If we add a tactile component, student hands substituted for the carts, the result is an anchor that was used in the Unit 9 lesson under discussion. However, two hands pressing on a spring still result in a brittle anchor. Experience with the curriculum indicates that

UNIT 9: NEWTON'S 3rd LAW	**Target (for Day 1): Moving Object Collides with an Identical Stationary Object (equality of forces)**	
This unit, in which the anchor in the third column was used on successive days for increasingly difficult targets, produced large gain differences on pre-post: 44.2 percentage points, compared with 14.5 percentage points for controls.	Failed Candidate Anchor #8: Log problem II: Mr. T is on the front of a railroad car colliding with another railroad car carrying a large log. Mr. T can choose which car will move and which will stay still. In which situation will he feel the greater force?	Anchor: Two hands push on two springs with a board between them; the left hand moves and the right hand remains stationary. On which hand is the greater force exerted?
A. CHOOSING CASES		
1) *(Validity)* **Find a case where students' predictions** concerning the variables of interest **are likely to agree with accepted physical theory**.	NO (53% on diagnostic)	YES (videotape evidence)
2) *(Conviction)* **Find a case where most students are intuitively confident** of the relationship between the variables of interest.	NO (43% on diagnostic)	YES (videotape evidence)
3) *(Imageability)* **Find a concrete case** evoking imagery that has kinesthetic and/or visual components.	YES	YES
4) *(Transferability)* Find a case for which students are able to transfer their intuitive knowledge about it into the target case.	NO (even when it did elicit valid intuitive knowledge, this knowledge failed to transfer in tutoring interview)	YES
a) Avoid "brittle" cases where a very small change in the case tends to cause a change in the intuition that is triggered for the students. E.g., avoid cases that rely on symmetry.	YES	YES
5) *(Explanatory potential)* Necessary for anchors used in learning pathways that lead to explanatory models. Find a case that:		
a) has a causal agent in it.	NO	YES
b) has a causal agent in it that can be simulated kinesthetically—allowing the student to build on the natural causality of his or her muscular system	NO	YES
c) allows the student to visualize causal aspects that are normally invisible in the target.	NO	YES (The position of the board reveals the equal amount of movement)

Table 4a.

	Failed Candidate Anchor #8: Log problem II	Anchor: Two hands push on two springs
B. CHOOSING OR IMPROVING (TUNING) CASES: increasing conviction, accuracy, or transferability through imagery enhancement		
1) *(Imagistic clarity)* **Find a case that does any or all of the following:**		
a) is as simple and schematic as possible (is easy to visualize mentally; is spatially manipulable).	PERHAPS (Students appeared to be able to visualize the case mentally, though it is not schematic)	NO (This case sacrifices some symplicity to add a marker; see below)
b) can *tap into intuitive kinesthetic or tactile knowledge* that most students have developed through their everyday bodily interactions with the physical world (e.g., most students can imagine pushing against a springy solid and imagine feeling the resulting push back against their hand).	YES	YES
c) uses "markers" (diagrammatic notation that makes variable differences easy to imagine or observe).	(The log was intended as a marker, though it did not work)	YES (the board serves as a marker to reveal the equal compression of the two springs)
2) *(Runnability)* **Find a case that:**		
a) is easy to run as a mental simulation (so that students find it easy to imagine the anchoring situation and to predict what will happen next).	YES	Perhaps not, but is demonstrable
b) allows the student to transfer runnability from the anchor to the target, to *see* mentally the similarity between results of running the anchor case and running the target case .	NO	YES

Table 4b.

students have trouble transferring their valid intuitions about this case to a case where only one hand moves. But, if we use two springs, add a board between them to be used as a marker to indicate the amount of compression undergone by each spring, then break the symmetry by having one hand remain still, the result is the case on the left of Figure 3, an anchor that worked (Clement, 1993). It was successfully used in the unit in conjunction with the otherwise brittle, symmetric case of two hands on a spring.

Attributes added were: 1. a spring *(A5a. causal agent)*, 2. a student's hands *(A5b. allowed causal agent to tap into kinesthetic and tactile imagery)*, 3. making the spring move rather than having the situation remain static as in the carts problems *(A5c. a way to visualize normally invisible causal aspects)*, 4. a thin board *(B1c. a marker to make normally invisible effects of the causal agent visible)*. The result is an anchor that has videotape evidence of producing conviction and accuracy (Clement, 1993). All that remains is 5. to have only one hand move *(A4a. breaks the symmetry)*. The asymmetric case also works as a classroom demonstration because of the presence of the marker (the board) that allows the effect of the causal agent to be seen clearly (both springs compress equally).

Comparison Two

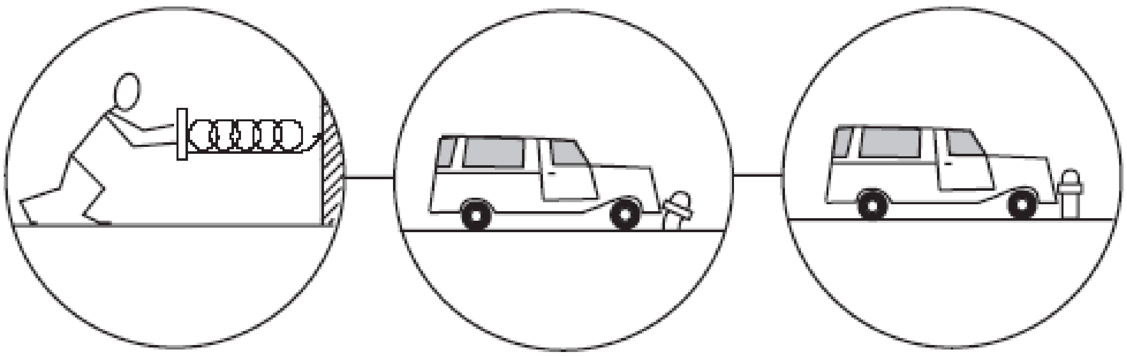

Figure 4. Analogy Diagram for a Unit 1 Anchor, a Bridge, and the Target

Fist Problem from the diagnostic test: You hit a brick wall as hard as you can with your fist. When your fist hits the wall:

- The wall exerts a force on your fist.
- The wall does *not* exert a force on your fist. The wall is just in the way.

This was a case that was expected to be a strong anchor. However, only 40% of respondents thought the wall would exert a force and only 22% were confident of this, far lower than the 70% response rate sought for an anchor.

The similar case in Figure 4, of a person pushing on a spring against a wall, was part of a successful sequence in Unit 1 that produced large gain differences on pre/post tests. (Pre-test scores averaged 24.7% correct answers and post-tests averaged 79.2% correct, for an average gain of 54.6 percentage points. The average gain in the control group was only 28.2 percentage points.) Note that though the target for the original fist problem was only to establish the existence of normal forces (which it failed to do), the modified case of Figure 4 became the principle anchor eventually used in the curriculum to establish—not only the existence, but—the *equality* of those forces. It may be seen as another example of how an unsuccessful anchor can be changed into a successful one by changing or adding elements and fine-tuning the imagery.

As with the successful anchor examined in the previous section, a change made to the original weak case here was to add a causal agent in the form of a bed spring. In this case also, the spring acts to mediate the forces, this time the forces between a hand or fist and a wall. It could be argued that the spring verges on becoming a global analogy for the curriculum, as air pressure was for the electricity curriculum mentioned earlier (Steinberg, et al., 1995). Although the spring is not used as an analogue in every unit, it is used as a visible mediator of forces in a number of the anchors. To each case, the spring lends its potential to elicit powerful visual and tactile imagery.

UNIT 1: NORMAL FORCES **Day 2**	**(existence of normal forces)**	**Target: Large Car Pushes on Fire Hydrant (equality of normal forces)**
This unit produced large gain differences on pre-post: 54.5 percentage points, compared with 28.2 percentage points for controls.	Failed Candidate Anchor #3: Fist problem. You hit a brick wall as hard as you can with your fist. Does the wall exert a force on your fist?	Anchor: Person pushes horizontally on a board on a spring attached to a vertical wall. Compare the force of the hand on the board to the force of the spring on the board.
A. CHOOSING CASES		
1) *(Validity)* **Find a case where students' predictions** concerning the variables of interest **are likely to agree with accepted physical theory**.	NO (40% on diagnostic)	(Not on diagnostic)
2) *(Conviction)* **Find a case where most students are intuitively confident** of the relationship between the variables of interest.	NO (22% on diagnostic)	(Not on diagnostic)
3) *(Imaegability)* **Find a concrete case** evoking imagery that has kinesthetic and/or visual components.	YES	YES
4) *(Transferability)* Find a case for which students are able to transfer their intuitive knowledge about it into the target case.	NO	YES
a) Avoid "brittle" cases where a very small change in the case tends to cause a change in the intuition that is triggered for the students. E.g., avoid cases that rely on symmetry.	YES	YES
5) *(Explanatory potential)* Necessary for anchors used in learning pathways that lead to explanatory models. Find a case that:		
a) has a causal agent in it.	NO	YES
b) has a causal agent in it that can be simulated kinesthetically—allowing the student to build on the natural causality of his or her muscular system	NO	YES
c) allows the student to visualize causal aspects that are normally invisible in the target.	NO	YES

Table 5a.

	Failed Candidate Anchor #3: Fist problem.	Anchor: Person pushes horizontally on a board on a spring .
B. CHOOSING OR IMPROVING (TUNING) CASES: increasing conviction, accuracy, or transferability through imagery enhancement		
1) *(Imagistic clarity)* **Find a case that does any or all of the following:**		
a) is as simple and schematic as possible (is easy to visualize mentally; is spatially manipulable).	YES	YES
b) can *tap into intuitive kinesthetic or tactile knowledge* that most students have developed through their everyday bodily interactions with the physical world (e.g., most students can imagine pushing against a springy solid and imagine feeling the resulting push back against their hand).	YES	YES
c) uses "markers" (diagrammatic notation that makes variable differences easy to imagine or observe).	NO	YES (The board can be considered a marker)
2) *(Runnability)* **Find a case that:**		
a) is easy to run as a mental simulation (so that students find it easy to imagine the anchoring situation and to predict what will happen next).	YES	YES
b) allows the student to transfer runnability from the anchor to the target, to *see* mentally the similarity between results of running the anchor case and running the target case .	NO	YES (Though one bridging case was used)

Table 5b.

Not withstanding the power of the imagery associated with the spring, another imagistic element has been added to the fist case, and that is a thin board. Students are encouraged to think of the force of the hand and the force of the spring as acting on the board instead of on each other. The curriculum asks, “What would happen to the board if one force were larger?” Thus, the board is designed to serve as a marker to make the changes in the variables of the case easier to observe. If the forces were not equal, the board could be seen to move.

Looking at Table 5, it can be seen that the main differences in coding for these two cases concern the lack of a visible causal agent in the wall for the first case (how can the wall produce a force?) and the lack of a marker to help make movement (or lack of movement) visible. It is hypothesized that these factors hinder the ability of the first case to elicit correct predictions or conviction in those predictions, or, where predictions are correct, to transfer the runnability of this case to the target.

For the second case, the causal agent is initially visualized as separate from the wall, residing, rather, in the spring. However, the unit concludes by encouraging students to see all matter as composed of particles connected with spring-like bonds. If students are able to predict that the hand and the spring are exerting equal forces on the board (once it stops moving), they stand a good chance of being able to transfer this understanding to the target case of a large car bumping a fire hydrant. The idea is to make available to students imagery of a microscopic causal agent that can render all matter capable of exerting equal and opposite normal forces on anything that compresses it.

Findings

It appears that the success of the anchors in the curriculum has to do with such factors as whether the changes in the variables of interest can be seen easily by the students, as well as other factors that appear to affect how successful the cases are in fostering the students' running of a mental simulation (e.g., being able to imagine the anchoring situation and predict what will happen next). Also, in some cases, success appears related to how successful the cases are in tapping into intuitive kinesthetic knowledge that most students have developed through their everyday bodily interactions with the physical world (e.g., pushing against a springy solid and feeling the resulting push back against their hand).

The list of strategies seeks to identify, describe, and clarify factors such as these, especially those that indicate characteristics held in common by anchoring cases that can be successful in instruction. The objective is to formulate a useable set of design principles. As we continue to hone the list, the following appears to be true:

- The strategies appear to characterize the successful anchors we have investigated.
- The principles highlight differences—some of them not obvious—between a selection of cases that have been shown to work as anchors, as evidenced by pre-post tests and/or positive performances on a diagnostic test, and those that performed poorly on the test.
- It was demonstrated that two cases unsuccessful as anchors, identified as similar to two successful anchors, could be viewed as transformations of the successful cases by application of strategies from the list. This bodes well for the ability of these strategies to suggest improvements to cases.
- Some of these differences help push the development of theory by generating hypotheses for why some anchors are less successful than others: e.g., an anchor that has a causal agent may be more convincing and able to transfer runnability more easily than similar cases that do not have this.

An unanticipated finding concerned the hand-on-spring case (Figure 1), used as an anchor on Day 1 of Unit 1. As we investigated the use of this case within the curriculum, it began to look somewhat like a "global anchor" in the sense that it was used in various ways—and incorporated into other anchors—in multiple lessons through out the curriculum, each of which dealt in some way with Newton's 3rd Law. The hand-on-spring case proved to be consistent with almost every design strategy in the list.

These findings lead us to believe that we have a good start on a set of design principles for successful anchors, which we believe can be used to:

- analyze additional anchors and predict their usefulness,
- design new anchors, and

- form an initial theory of how and why anchors work.

The headings of the strategies in Table 2 should convey the sense in which we are attempting to develop a theory of characteristics for cases that can successfully ground scientific models in students' prior knowledge schemas. Aided by studies of expert model construction, this attempt includes developing vocabulary to describe the role of imagistic mental simulations and physical intuitions in grounding the meaning of scientific models so that they make sense to students. This is a section of the foundation of conceptual change and modeling theory that has largely been missing.

We stress that, though our list of identified characteristics should help considerably to identify potential anchors and weed out cases not likely to work, the anchors still need to be developed through testing on students. However, we are encouraged that this list appears to work well in revealing sometimes subtle differences in the design attributes of successful and unsuccessful cases for anchors.

Implications

The fact that the success of the anchors appears related to such factors as their success in fostering the running of mental simulations and their success in tapping into kinesthetic knowledge should have implications for any pedagogical theory of conceptual change.

On the practical level, these findings have implications for the design of lessons to address persistent student misconceptions. We believe this can be achieved through the creation of analogical sequences that foster students' accession and transfer of relevant prior knowledge along the entire bridge of analog cases and into the target case, often against their own initial intuitions about the target. Our findings also have implications for the development of teaching strategies to implement such lessons in the classroom.

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