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Using Bridging Analogies and Anchoring Intuitions to Deal with Students' Preconceptions in Physics

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Abstract

Lessons were designed to deal with students' alternative conceptions in three areas of mechanics: static normal forces, frictional forces, and Newton's third law for moving objects. Instructional techniques such as class discussions of the validity of an analogy between a target problem and an intuitive anchoring example, and forming a structured chain of intermediate bridging analogies were used. There were large differences in pre–posttest gains in favor of the experimental group. In formulating a model of learning processes that can explain these results, it is argued that (a) the lessons have a more complex structure than a simple model of analogy use; (b) rational methods using analogy and other plausible reasoning processes that are neither proof based nor directly empirical can play a very important role in science instruction; (c) much more effort than is usually allocated should be focused on helping students to make sense of an analogy; and (d) researchers and curriculum developers should be focusing at least as much attention on students' useful prior knowledge as they are on students' alternative conceptions.

This article discusses the use of analogies and other instructional strategies in dealing with students' preconceptions in physics. In order to discuss students' conceptions and their relationship to instructional strategies, it is important to clarify some of the terms to be used. Because the context here is instructional strategy development, the term *preconception* will be used to mean a conception in a certain area that is present in a student prior to instruction. It is important to emphasize that not all preconceptions are misconceptions. The lessons to be discussed here are also based on preconceptions that are largely in *agreement* with currently accepted theory. Here these will be termed *anchoring conceptions* (Clement, Brown, & Zietsman, 1989).

Alternative conceptions (misconceptions) are used here for conceptions that can conflict with currently accepted scientific theory. There has been some controversy over whether to call these misconceptions, alternative conceptions, or something else. A potential problem with the term *misconception* is that it might suggest a negative connotation with respect to the worth of the student's self-constructed ideas and thought processes. Such conceptions should be respected as creative constructions of the individual, and in some cases they are successful adaptations to practical situations in the world. The problem with the term *alternative conception* is that it can be taken to mean that all ideas are equally useful in all contexts, which is not true. In some contexts naive subjects can have maladaptive beliefs, such as misconceptions about disease transmission.[1]

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Probably the most important need is to define precisely the terms that one uses. Here I suggest that a useful definition for both of the terms *misconception* and *alternative conception* (treated here as synonyms) is the one I have used in the past for *misconception:* a conception that can conflict with currently accepted physical theory. This definition avoids implying that the expert has found truths with absolute certainty or that the naive student's ideas are worthless and unimprovable. In this article I will favor the term *alternative conception.*[2] In the context of a course on Newtonian mechanics, student errors or correct answers are defined in a similarly neutral way with respect to their agreement with Newtonian theory.

By *changing an alternative conception* or *conceptual change* here I mean overcoming the dominance of an alternative conception in inappropriate situations in some way; thus it could mean *modify the domain of, displace, modify and improve, replace, or suppress* a conception, depending on what is most appropriate.

The Problem of Alternative Conceptions

There is now considerable evidence that students in physics courses experience significant conceptual difficulties at a qualitative level in addition to the challenge of learning quantitative concepts. Patterns in the errors on qualitative problems indicate that the errors are not random. Along with interview data, they suggest that students are not simply failing to learn new material, but have alternative conceptions about it. Pretests and interviews given prior to the course show some of the same error patterns and indicate that students are entering courses with alternative preconceptions. Collected evidence for these findings can be found in Driver and Easley (1978), Driver and Erikson (1983), McDermott (1984), Pfundt and Duit (1991), Helm and Novak (1983), and Novak (1987), among others. Similar data taken after courses indicate that some of these preconceptions do not change much and constitute persistent barriers to achieving conceptual understanding (Minstrell, 1984). This can even occur for large numbers of students in calculus-based college physics courses, even though they may be proficient at the use of physics formulas (Clement, 1983; Halloun & Hestenes, 1985). This indicates that courses need to place increased emphasis on dealing with alternative conceptions.

Deep Seatedness. It is clear that some alternative preconceptions are more deep-seated than others. As Chaiklin and Roth (1986) point out, incorrect answers to diagnostic problems may not always reflect deeply held preconceptions, because students are willing to use beliefs they are uncertain about in problem solving. However, there are several different types of evidence indicating that some alternative preconceptions are deep-seated, in addition to the pre–postcourse tests cited above. Confidence measures provide some evidence: Brown and Clement (1987) found that students indicated they were fairly confident in their incorrect answers on a set of qualitative problems in the area of Newton's third law of "equal and opposite forces" after taking high school physics. Other indications of deep-seatedness include spontaneous expressions of conviction in interviews, resistance observed during tutoring (Brown & Clement, 1989), and historical parallels to students' alternative conceptions (Clement, 1982; Steinberg, Brown, & Clement, 1990; Wiser & Carey, 1983). The latter indicate that the students are in good company; Westfall (1980), in his extensive, historical-cognitive biography, interprets Newton's records as showing how certain persistent preconceptions, including impetus and centrifugal force, were mutually supporting and showing that they held Newton back for up to 20 years before he was able to finish the *Principia.*

A few initial attempts to deal with students' alternative conceptions in physics have met with mixed but in some cases encouraging success (Brown, 1987; Halloun & Hestenes, 1985;

McDermott, 1984; Minstrell, 1982) and researchers are beginning to formulate a variety of strategies (Scot, Asoko, & Driver, 1992). However, studies of in-depth interventions in specific content areas are needed in order to assess the different strategies being proposed.

Teaching Strategy Used in this Study

The method used in this study for helping students deal with persistent alternative conceptions attempts to have students build up their understanding at a qualitative, intuitive level before mastering quantitative principles. It also encourages students to become aware of their own alternative conceptions, to actively criticize them, and to develop new conceptions.

The technique can be illustrated by describing a lesson used to address the alternative conception of *static objects as barriers that cannot exert forces*. The classic target problem in this case is the question of whether a table exerts an upward force on a book placed on the table. Observations from classroom discussions and tutoring interviews indicate that many students believe that static objects such as the table are rigid barriers that cannot exert forces. In a diagnostic test, 76% of a sample of 112 high school students indicated that a table does not push up on a book lying at rest on it. (These were chemistry and biology students who would be eligible to take physics in the following year.) On the other hand, 96% of these students believed that a spring pushes up on one's hand when the hand is pushing down on the spring. For physicists, these two beliefs are incompatible because they see the two situations as equivalent.

diSessa (1983) refers to the concept of springiness as a "phenomenological primitive" and describes acquiring skill in physics as depending on the evolution of such intuitions. The hand-on-the-spring situation is a useful starting point for instruction because it draws out an intuition from students that is largely in agreement with the physicist. For this reason it is called an anchoring example that draws out an anchoring conception. Such intuitions may be articulated or tacit.

A Strategy that Failed

A reasonable strategy would be to present the hand-on-the-spring and the book-on-the-table problems to students and ask them if they are not indeed analogous. When students see that the table is analogous to a spring they should change their view of the book on the table situation. Unfortunately, pilot tutoring interviews conducted by David Brown have indicated that this simple strategy does not often work. Instead, students typically say that the table is not at all the same as a spring—the table is rigid or dead, whereas the spring is capable of returning to its original position and pushing back—so the spring can exert a force, whereas the table cannot. Thus there is a need for an additional effort to help students see how the analogy between the spring and the table can be valid. This effort fits with the more general plea of Posner, Strike, Hewson, and Gertzog (1982) to make science ideas plausible to students (e.g., having it make sense that tables push up) as well as comprehensible (knowing that tables push up). Minstrell (1982) has reported some success in using key examples in Socratic teaching for the book-on-the-table problem. In what follows we will build on his ideas by adding an explicit emphasis on anchoring intuitions, structural chains of analogies, and mechanistic models in such lessons.

Applying an Expert Learning Strategy Using Bridging Analogies

The spontaneous use of analogies has been documented in think-aloud interviews with scientists (Clement, 1981, 1988), and with students (Clement, 1987). Experts have also been observed to use special patterns of analogical reasoning in order to stretch the domain of a key

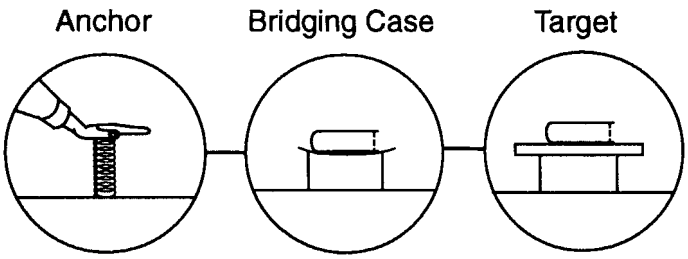

Figure 1. A bridging analogy.

analog example, confirm the validity of an analogy, and overcome a conceptual difficulty (Clement, 1986, 1989). It was conjecture that these patterns might be useful for overcoming conceptual difficulties in students as well. Examples of these patterns applied to the normal forces area are identifying salient features that are the same in the book and the spring; showing the existence of a conserving transformation between the book and the spring; and using a technique called bridging, described below.

Figure 1 shows a thin flexible board case used to help students determine that the analogy between the hand-on-the-spring anchor and the targeted book-on-the-table case is valid. The strategy of finding an intermediate third case that shares features with both the original case and the analogous case is termed a *bridging analogy.* Here, the idea of a book resting on a flexible board (case B) shares some features of the book on the table (case C) and some features of the hand on the spring (case A). The subject may then be convinced that A is analogous to B and that B is analogous to C with respect to the same important features, and thereby be convinced that A is analogous to C. Such bridges are not deductive arguments, but experts have been observed to use them as a powerful form of plausible reasoning (Clement, 1986). Presumably, this method works because it is easier to comprehend a close analogy than a distant one; the bridge divides the analogy into two smaller steps that are easier to comprehend than one large step.

Method

In this study several lessons were constructed around the bridging-from-anchors strategy and tested against control groups to see whether progress could be made in areas where persistent alternative conceptions exist.

Sample

Subjects were high school students taking a first-year physics course. The study involved three experimental-group teachers in two high schools and two control-group teachers in two other high schools. The experimental group consisted of 150 students and the control group contained 55 students. Experimental-group teachers participated in a 1-week workshop on the lessons during the summer in the pilot and experimental years.

Intervention

Experimental lessons were constructed by a design team consisting of David Brown, Charles Camp, John Clement, John Kudukey, James Minstrell, Klaus Schultz, Melvin Stein-

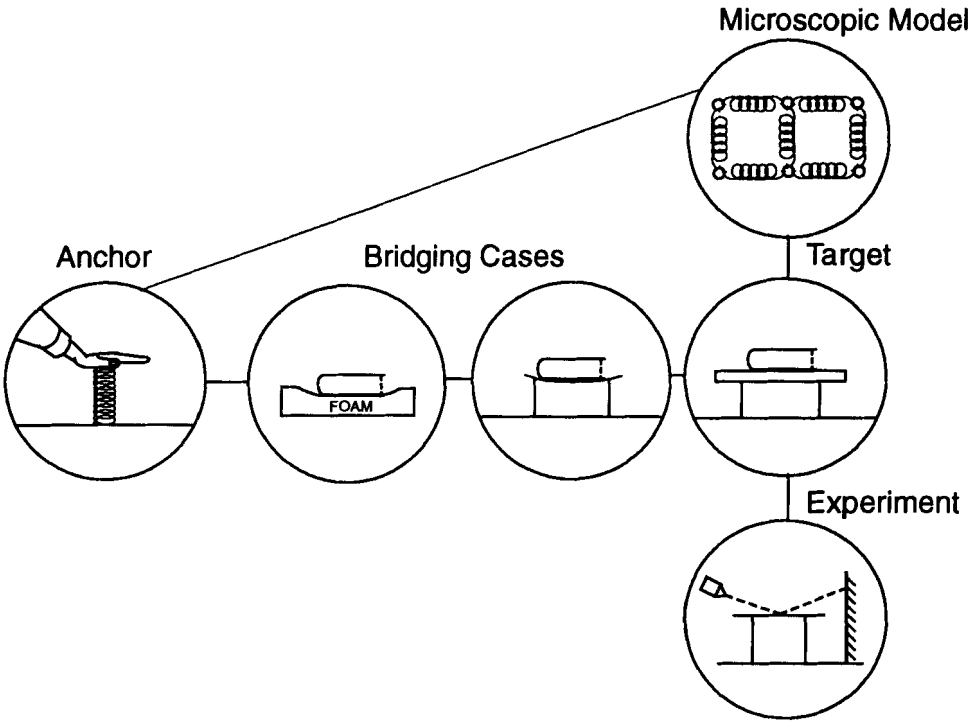

Figure 2. Concept diagram for static normal forces.

berg, and Valerie Veneman. The lessons were pilot tested for 1 year and revised on the basis of classroom observations. Updated versions of these lessons can be found as three of the nine units in Camp et al. (in press).

The experimental lessons sometimes used more than one intermediate bridging case; as shown in the concept outline of the lesson on static forces in Figure 2, a second bridging case of a book on a flexible foam pad was used. The analogies were not presented to the students in a lecture. During the lesson, the class compared each of the thought experiment examples in a discussion led by the teacher. As each case was introduced, the teacher challenged students to say why they believed that cases were similar or different and did not share the physicist's view until near the end of the class.

Normal Forces Unit. In this unit students first conducted a laboratory exercise in which they became familiar with various properties of springs. In the next lesson, outlined in Figure 2, the target problem—the question of whether the table pushes up on a book—was introduced first. Then the hand-on-the-spring case was discussed and agreed upon as an anchor. Students were asked for similarities and differences between it and the book-on-the-table situation. The bridging cases of the foam pad and flexible board were introduced next, and students were asked to compare them with the spring and the table cases. Toward the end of the lesson the teacher introduced a microscopic model of rigid objects as being made up of atoms connected by springlike bonds. Finally the students viewed a demonstration where a light beam reflecting off of a mirror on a desk onto the wall is deflected downward when the teacher stands on the desk. After establishing the existence of a normal force in the first lesson, the equality of forces in such cases was addressed using similar techniques in a second lesson.

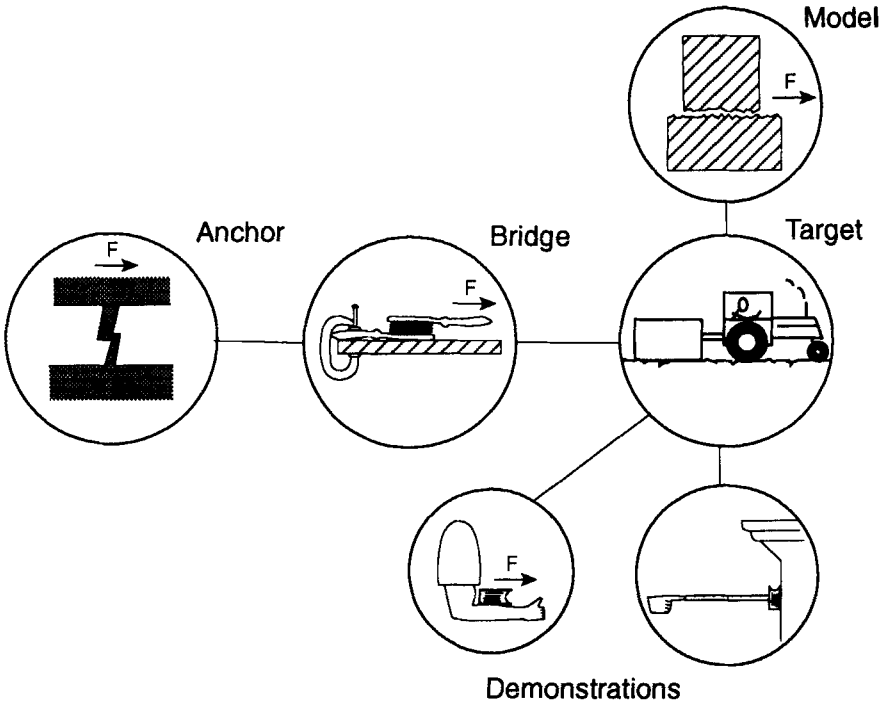

Figure 3. Concept diagram for surface friction.

Friction Unit. In a second area, the lesson on friction outlined in Figure 3 used the target problem of a heavy box being pulled over the ground by a tractor. Students were asked the directions of the forces acting on the box. Many students either fail to identify a force of friction, or say that friction has no particular direction or that it acts in a downward direction. On the other hand, the physicist identifies a force of friction exerted by the floor on the box acting horizontally to the left. The bridging example introduced in this lesson was a brush being pulled to the right while resting on top of another brush as shown in Figure 3. The anchor situation in the leftmost drawing was the same experiment with only two single bristles on each brush. Most students thought that the lower bristle would exert a horizontal force to the left on the upper bristle. The cases were compared in discussion as described for the first lesson above. The teacher also introduced a microscopic model of surfaces as being very rough (somewhat like brushes) in a microscopic view. Other more complex models of friction such as "temporary welds" and Van der Waals forces were included at the end of the lesson to extend this oversimplified model, but the sequence in Figure 3 was used first to motivate an intuition for the direction and equality of the forces. Toward the end of the lesson these concepts were applied to a demonstration where students were asked about forces on a book placed on a student's arm resting on a desk. As the teacher pulled the book gently toward the student's hand, but not hard enough to make it slide along the arm, the class was asked whether the arm was exerting an opposite force on the book. The issue of *equal* and opposite frictional forces was then discussed using the same anchor and target examples.

Third Law Unit. As a third example, a lesson on Newton's third law in moving objects used a target problem of a moving cart colliding with a stationary cart of the same mass, as

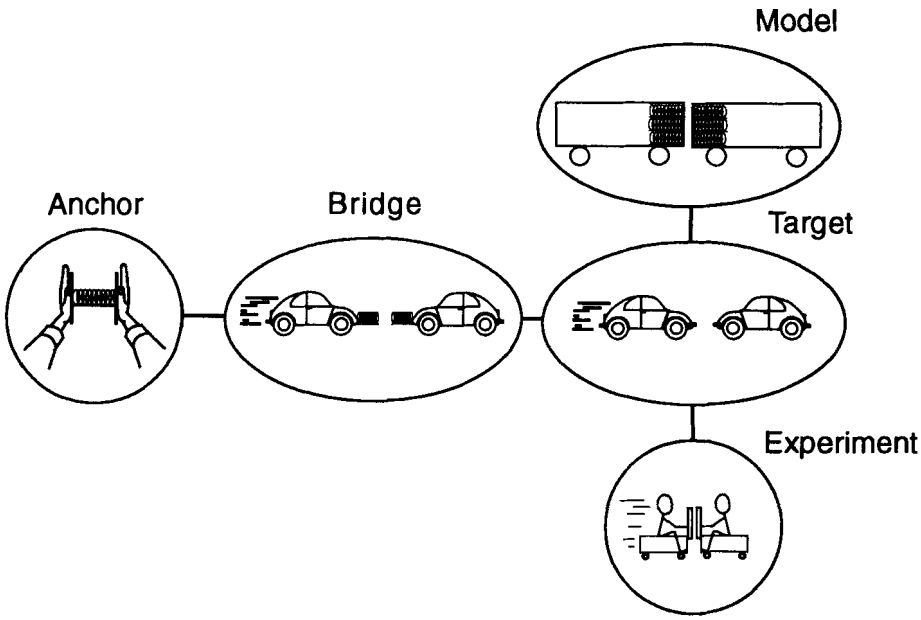

Figure 4. Concept diagram for dynamic third law.

shown in Figure 4. The anchoring example here drew on the idea that both of one's hands feel the same force when compressing a spring between them. The bridging example was a pair of colliding momentum carts, where one cart has a spring attached or contains a spring-loaded plunger. Students were asked to discuss whether the force on cart A is the same size as the force on cart B. They were then asked if this is equivalent to the target problem if one considers the surface of cart B to made up of springlike bonds between its atoms (a microscopic model). At the end of this lesson an experiment was done where a student riding on a projection cart collided with another student on a stationary cart. Bathroom scales held by each student out in front of the carts received the impact of the collision. Students predicted whether one reading would be consistently larger. These give very rough measurements, but they are accurate enough over several trials to provide conflict for students who hold that the forces will be quite different. The second lesson extended this idea to unequal masses using similar questions.

Thus the lessons used a sequence of analogous cases to connect an anchoring example to the target problem, and also to develop a visualizable model of the mechanism(s) providing forces in the target problem. Demonstrations were used primarily to disequilibrate students' alternative conceptions or to support an aspect of the analog model such as the presence of deformation in rigid objects. Experimental-group students were given two one-period lessons on normal forces, one on friction, and two on the dynamic third law. Discussions of homework and quiz questions took up to one additional period in each of three units. The lessons were introduced at the different points where they fit into the students' study of mechanics during the year. Control-group classes studied their normal curriculum.

Data Collection

The teaching strategy described above was evaluated by giving identical pre- and posttests to experimental- and control-group classes. The test instrument, described in Brown and Clement (1987), consisted of 15 questions designed to detect common alternative conceptions in

each of the three areas and contained both near and far transfer questions. In a previous year, clinical interviews were conducted on each question and modifications were made to repair or replace questions and answer choices that were not reflective of the students' conceptions. Identical pre- and posttests were given about 6 months apart: in the second month of the course just before the first experimental lesson (on static normal forces) and again about two months after the final experimental lesson (on the dynamic third law). Thus the retention periods measured by the posttests were 2 months or more for all lessons. All teachers were blind to the problems on the tests.

Quantitative Results

Results are shown in Table 1. It should be emphasized that the physics topics under consideration here are extremely basic, and are part of the assumed foundation of qualitative concepts that quantitative concepts in physics must rest on if they are to have any meaning. Thus the post scores for the control group indicate rather severe difficulties in the students' conceptual understanding after instruction.

The experimental group achieved significantly larger pre–posttest gains than the control group in each of the three lesson areas. The difference between the gains was on the order of 1 standard deviation in each area. Taken together, the lessons produced an average gain difference of 27.5% or about 1⅓ standard deviations ($t = 8.41$, two tailed, $p < .0001$).

The pretest scores in the experimental group were somewhat higher than those in the control group. Although this is taken into account by focusing on gain scores, it would still be desirable to eliminate this difference. Fortunately, one of the experimental-group schools and one of the control-group schools had upper- and lower-level classes, whereas the other schools had students grouped homogeneously. This allowed us to look at an experimental group with lower

Table 1
Gains for Control ($n = 55$) Versus Experimental ($n = 150$) Classes

	Pretest	Posttest	Gain
Static normal forces (Points possible = 6)			
Control	1.99 (16.59%)	2.69 (44.8%)	1.69 (28.2%)
(S.D.)	(1.07)	(1.80)	(1.65)
Experimental	1.48 (24.7%)	4.75 (79.2%)	3.28 (54.6%)
(S.D.)	(1.63)	(1.02)	(1.65)
Experimental group showed larger gains ($t = 5.91$, two-tailed, $p < .0001$)			
Friction forces (Points possible = 3)			
Control	0.23 (7.9%)	0.65 (21.8%)	0.41 (13.9%)
(S.D.)	(0.51)	(0.78)	(0.85)
Experimental	0.36 (11.9%)	1.58 (52.7%)	1.22 (40.6%)
(S.D.)	(0.61)	(1.01)	(0.98)
Experimental group showed larger gain ($t = 5.33$, two-tailed, $p < .0001$)			
Dynamic third law (Points possible = 6)			
Control	1.24 (20.7%)	2.11 (35.2%)	0.87 (14.5%)
(S.D.)	(1.15)	(1.50)	(1.29)
Experimental	1.56 (26.0%)	4.21 (70.2%)	2.66 (44.3%)
(S.D.)	(1.43)	(1.58)	(1.85)
Experimental group showed larger gain ($t = 6.54$, two-tailed, $p < .0001$)			

pretest scores. When the lower-level experimental-group classes (with a person relatively new to physics teaching) were compared to the homogeneous control classes (with a person considered to be a master physics teacher), there were still significant differences larger than 1 standard deviation in each area in favor of the experimental group ($p < .0001$ in each case, Clement et al., 1987).

As much care as possible was given to picking control teachers who were as competent as the experimental-group teachers. (One of the control-group teachers was voted best physics teacher in the state in a previous year. The other control-group teacher had been selected to be involved as an experimental instructor in another NSF project in previous years.) Both were quite experienced and had excellent reputations. Two of the three experimental-group teachers, on the other hand, had taught physics for 2 years or less, having previously taught biology in one case and junior high science in the other.

One opportunity arose to check on the influence of the teaching skill and school location variables. One of the experimental-group teachers had been a control-group teacher during the initial classroom trials in the previous year. For this teacher comparable data were collected from two lower-level physics classes during each year. In the first year the teacher used their normal curriculum; in the second year the experimental lessons were used. The experimental-group students had significantly larger gains in two of the three areas, showing gain differences of about 1¾ standard deviations over control students in static normal forces ($t = 7.75$, two-tailed $p < .001$) and the dynamic third law ($t = 7.51$, two-tailed, $p < .001$). Although their gains in the friction section were not significantly higher, it was encouraging that considerable gains could be measured in two areas with lower-level physics classes.

Qualitative Results

Qualitative observations from videotapes of these classes indicate that

1. Students appear to readily understand the anchoring cases.[3]
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, for example, 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 that provides further support for this hypothesis).
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.

Summary

Experimental classes did not achieve high posttest scores on all transfer problems. And discussions in different classes varied somewhat unpredictably from dull to very exciting. Thus there is still considerable room for improvement. Nevertheless, the results are strong enough to suggest that the time devoted to the techniques being tried is having an effect in helping students change their alternative conceptions.

The findings can be summarized as follows:

1. The experimental-group students achieved much larger gains than control-group students on an instrument designed to detect alternative conceptions in physics.
2. Surveys conducted in class by the experimental-group teachers indicated that the behavior of the anchoring example introduced at the beginning of the lessons was comprehended correctly by most students after a short discussion. However, many students were not confident that it was analogous to the target at this stage, and the anchoring analogy was insufficient on its own to change most students' responses to the target question. Apparently the subsequent bridging analogies, explanatory models, and demonstrations were important in producing the gains achieved.
3. Some process goals were achieved during the instructional process as well.

Discussion of Results

One reason that the above results must be carefully stated is that experimental groups spent more time on the topics than control groups. However, other studies have shown that increasing instructional time alone has a discouragingly small effect on alternative conceptions concerning force and motion. Minstrell (1984) investigated different methods for teaching about the effect of forces on moving objects. In his study pretest scores on two questions in this area averaged 3% correct. Posttest scores on these problems after traditional instruction methods were used were 62% and 36%. His major finding was that increasing the care and time spent on this topic from 2.5 to 4.5 weeks in a subsequent year led to only very small gain differences of (7% on each question for the students studied). This surprising and discouraging result from a master physics teacher is indicative of the persistence of these alternative conceptions in many students. Also, we measured no gain differences over controls in a first year's trial on other lessons using extra time (Brown & Clement, 1991). This suggests that additional time on topic is not a sufficient condition for dealing with persistent alternative conceptions.

Because of the difficulty of the problem of dealing with such conceptions, it was decided that the goal for the present study should be to investigate whether some progress on this problem is possible, by whatever reasonable means. Because there is a widespread opinion within the physics teaching community that deeper conceptual understanding in these areas will require more instructional time, the first question to be addressed was whether such an investment of time can produce any results. (Minstrell has since achieved much better gains by using nontraditional methods in addition to increasing the time spent.)

A second possible criticism of the study is that the tests were multiple-choice tests, and more accurate assessment of conceptual change requires clinical interviewing methods. However, we have more recently obtained significant gain differences and clinical interview evidence for conceptual change in individual learning studies (Brown, 1992). This study used very similar instructional methods in the area of static normal forces. Brown's treatments controlled for the length of the intervention and did not use laboratories or demonstrations, allowing him to implicate the nonempirical instructional strategies of analogies, bridges, and models as probable

sources of conceptual change. We have also obtained significant gain differences over controls in clinical learning studies in the area of lever concepts. That study was conducted at the seventh-grade level and used the strategies of analogies, models, and extreme cases (Zietsman, 1990).

General Discussion

This more theoretical section goes beyond direct inferences from the present data to hypothesize characteristics of the learning processes fostered by the instructional strategies used. I will begin by discussing the instructional strategy in terms of a simple, "basic" model of analogical reasoning as transfer of information from a source to a target. I will then discuss how the structure of the lessons is also intended to foster learning processes that are more complex than this simple form of analogy use.

Enhancing the Simpler, Basic Model of Learning by Analogy

Figure 5 shows the elements of a basic model of analogical reasoning. Efforts are made to find a case A that can be seen as analogous to the target case T. (The initial lack of understanding of T is indicated by a dotted circle.) There are then three major requirements for comprehending the intended analogy: (a) students must understand case A with some degree of conviction, and (b) they must confirm the plausibility of the analogy relation S (the initial uncertainty in this plausibility is indicated by the dotted line.) That is, they must come to see case T as similar to case A in the intended ways, and (c) they must apply findings from case A to case T.

Research Needed on Anchors. With respect to the first requirement above, I have emphasized the need to search for anchoring intuitions. The notion of searching for anchoring intuitions opens up a large field of needed research that should complement the ongoing research effort on alternative conceptions. Potential anchoring examples can be listed by skilled teachers, but they require empirical confirmation. For example, our team confidently predicted that hitting a wall with one's fist would be an excellent anchoring example for the idea that a static object can exert a force. Surprisingly, however, only 41% of prephysics students tested agreed that the wall would exert a force on one's hand. Thus empirical studies are needed to find good anchors—not just any concrete example that makes sense to the teacher will work. This should forewarn lesson designers using analogy from basing their work only on an armchair analysis of a topic. (In areas where students have insufficiently developed anchoring intuitions they may need to be developed by real or simulated experiences such as Arons's (1990) activity of having students push large objects in a low-friction environment, McDermott's (1984) use of air hoses to accelerate dry ice pucks, or the diSessa, Horowitz, and White use of dynaturtle, White, 1983).

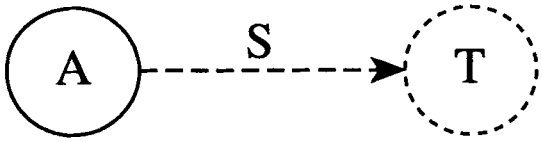

Figure 5. Simple model of analogical reasoning.

Beyond the Simple Model of Learning by Analogy

Bridging as Plausible Reasoning versus Formal Proof. It was observed that the anchors used in these lessons were not initially deemed to be similar to the target problem by many of the students. This indicates that cases that are obviously analogous to the teacher may not appear analogous at all to students without considerable additional thought. Intermediate bridging examples were used to bridge this gap. This method may work because the bridge divides the analogy into two smaller pieces that are easier to comprehend than one large piece. Thus, forming structured chains of bridging analogies is a way in which these lessons go beyond a simple model of analogy use. Our observations of classrooms indicate that much more effort than is usually allocated must be devoted to making analogies plausible to students.

Polya (1954) identified a set of important plausible reasoning strategies in mathematics. More recently, it is becoming recognized that thought experiments and analogies are important plausible reasoning strategies used in science (Harre, 1961; Hesse, 1966; Nersessian, 1984). Bridging analogies are a form of plausible reasoning process that has only recently been documented in experts solving scientific problems (Clement, 1986, 1989). As in the case of experts, the bridging cases used here appear to work with knowledge representations that are qualitative physical intuition schemas, not at a level that uses formal notations. Bridging appears to be an important tool for stretching the domain of applicability of an anchoring intuition to a new situation, that is, for making the intuition more general and powerful. Analogies and bridging may therefore be important plausible reasoning strategies for developing and refining physical intuitions. It may be that such selected plausible reasoning processes are more powerful than logical proof processes for the development of qualitative ideas that make sense to students.

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. Presumably what makes this possible is that the student's knowledge schemata are "packaged" in much smaller pieces than the physicists' knowledge (diSessa, 1983), and that each schema is activated in different contexts. The teaching strategy takes advantage of this fact by using discussion and bridging examples that can belong to either context, to promote dissonance between the anchor and the alternative conception, thereby encouraging conceptual change. 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 as being about something unusual to be learned.

Overall Lesson Structure. The concept diagrams for the lessons, shown in Figures 2–4, depict some of the different levels of knowledge that the lessons focused on. The most central level in these lessons contains a set of carefully chosen thought examples or cases for discussion, including a target example, an anchoring example, and one or more bridging examples.

Explanatory Models. Whereas the examples in the middle level of the concept diagrams are specific thought examples, the upper level contains more general *explanatory models* such as the visualizable mechanism of springlike bonds between atoms in Figure 2. This is a second way in which the strategy differs from a simple analogy. Explanatory models differ from specific analogous cases in several ways. Rather than being a specific case, they are the image of a mechanism that is assumed to be present in many cases. Ideally, a well-understood model can be projected into any of the specific cases below it in the diagram. They are ordinarily constructed during instruction and not simply retrieved as a familiar example from memory. Nor are such models simply a set of common features abstracted from observed phenomena (one cannot observe atoms or bonds inside of tables). Like other explanatory models in science they are imagined constructions (Brown & Clement, 1989; Hesse, 1966). Other interesting examples of explanatory model development appear in Steinberg (1992), and Zietsman (1990).

The Role of Empirical Investigation in the Lessons

Empirical Investigations and the Role of the Concept Diagrams in Lesson Design. In contrast to the thought experiments, actual demonstrations and laboratory experiences are shown at the lower level. Although the demonstrations in these particular lessons tend to speak to the target question, demonstrations and labs in other lessons could be used to support other elements such as an anchor or bridging case that needs added support. Seeing the structure of the lesson in the concept diagram can help one decide how and when to use a lab or a demonstration in the sequence of activities in the unit. Elements are not always introduced from left to right in the diagram, but the connections between elements are attended to carefully in designing a lesson. Thus, concept diagrams like Figures 2–4 were found to be a valuable tool for the process of lesson design. Physics lessons have a tendency to become a series of disconnected activities for students; the concept diagrams can also help remind teachers and students of the larger argument structure of the lesson. Overall, the diagrams illustrate how each lesson uses a three-pronged approach to helping students construct a new conception of the target problem, involving thought experiments, explanatory models, and empirical experiences.

Demonstrations and Laboratories Not More Central than Other Methods. In giving workshops for high school and college teachers on constructing lessons for dealing with alternative conceptions, our group has found that many physics teachers will try to find a single, quick demonstration that will remove the alternative conception and/or convey the physicist's conceptions. However, demonstrations that provide direct evidence for the physicist's qualitative models in these areas are hard to find. This makes sense, because if one is trying to help students develop a theoretical, explanatory model of a nonobservable process such as elastic or frictional force production, the model itself will not be amenable to direct demonstration.[4] A demonstration is included at the end of most of the present lessons for other purposes, but none were built around a demonstration that provided conclusive evidence for the physicist's model. Instead, the lessons focused more energy on the development of analogy relations and conceptual understanding than is ordinarily done, and rational arguments were fostered at least as much or more than empirical ones. Brown (1992) obtained evidence for conceptual change in tutoring interviews on static normal forces without using any demonstrations or laboratories. Evidence for change was also found for students using the above strategies minus demonstrations and laboratories in an instructional computer program described in Murray, Schultz, Brown, and Clement (1990). Thus it appears to be possible to affect students' alternative conceptions in some cases

without relying on laboratories or demonstrations as a dominant method. Our current hypothesis is that demonstrations and laboratories can and should play a powerful role in instruction but that they are only a piece of what is needed. It is interactions between empirical and rational processes that are sought. Discussions of rational thought-examples not only tap important anchoring conceptions; they may raise questions and conflicts that prepare students to see the significance of a demonstration and to think about it and discuss it actively rather than memorizing the result. Thus rational methods using analogy and other plausible reasoning processes that are neither proof based nor directly empirical play a very important role in this approach.

Conclusion

Learning as Interaction Versus Reception

The approach described above focuses time and effort on the development of qualitative conceptual understanding and uses analogies as a central technique. However, much more effort than is usually allocated goes into the development of these analogies and the method goes beyond a simple model of analogy use.

This approach—which relies on a mixture of problem solving, demonstrations, small-group labs, and especially large-group discussion—can be viewed as a form of guided constructivism. The method lies midway between pure didactic and pure discovery techniques. Because the development effort focused on content goals, a set of target, anchoring, and bridging case problems are chosen carefully for introduction by the teacher into large-group discussions, and certain elements such as microscopic models are introduced didactically on occasion. In this way the method certainly is more structured than an open discovery technique.

However, students also bring familiar and sometimes creative examples into discussions, and the teacher is very careful to promote and encourage discussions for a considerable period of time without revealing his or her position on the target problem. Although the teachers introduce target and anchoring examples into the discussion, they do *not* reveal their opinion on whether the anchor is analogous to the target problem. Thus *the students are actively engaged in evaluating whether the examples are analogous or not and in finding the best way to view the target situation,* and this is encouraged further by having them vote on issues periodically during the discussion.

In this way the method departs significantly from purely didactic methods and from a model of teaching where knowledge is "piped directly into the empty vessel" of the student. It does so by drawing out prior knowledge in the student and interacting with it in a number of ways rather than simply transferring knowledge. It interacts with prior knowledge of two types: anchoring intuitions that are in agreement with accepted theory and alternative conceptions that are not. These interactions take the form of conflicts between these two types of knowledge within the same student, various interactions with ideas from other students and the teacher, and evaluation of ideas in the light of empirical experiences. Thus the lessons emphasize interaction with the prior knowledge and reasoning abilities of the students as a form of guided constructivism.

Summary of Teaching Strategies

In addition to the techniques of demonstrations, laboratories, and problem solving, the special techniques used in the teaching approach investigated here were

1. *Anchoring examples* that tap intuitions that are largely in agreement with accepted theory can be used as starting points, showing that not all preconceptions are miscon-

ceptions. An important agenda item for research is the need to search for such anchoring intuitions.

2. *Forming analogies* between more difficult examples and an anchoring situation is an important instructional technique. However, more energy than is commonly realized must be invested in helping students to believe in the validity of such analogies.
3. Two techniques for doing this are *bridging* by using structured chains of intermediate analogies combined with *group discussions* to encourage active thinking.
4. *Explanatory models* can be constructed from anchoring examples to provide an imageable mechanism that explains the behavior of the target case.

Methods 3 and 4 involve learning processes that are more complex than those described by simpler models of learning by analogy. All four methods involve rational processes of plausible reasoning that have been observed in expert scientists (Clement, 1991). The theoretical viewpoint that guided the construction of the lessons is that such processes are central to the development of conceptual understanding and provide an important complement to empirical investigations and mathematical proof as modes of learning. More detailed investigations of exactly how these processes contribute to learning is an important topic for future research.

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Notes

[1] A second problem is that when one wants to refer to ideas like persistent alternative conceptions one ends up with a rather long phrase. One option is to call them PACs, creating a parallel that might please our founding fathers in the U.S., but I will resist that temptation here.

[2] In fact, students may exhibit a spectrum of ideas: those which are diametrically opposed to the physicist's ideas, those which are only partially conflict with physicist's ideas, and those which are largely in agreement. Also, in many cases one is dealing with a *set* of possible preconceptions brought to bear on a problem rather than single preconception. However, in order to simplify the discussion here, I will retain the definitions used. It should be noted that preconceptions and alternative conceptions are partially overlapping sets, because some preconceptions are anchoring conceptions, and some alternative conceptions may develop during, rather than prior to, instruction.

[3] The anchoring example of brush bristles in the friction lesson does not produce quite as much consensus as one would like, but as yet we have not been able to find a better anchor.

[4] An exception is cases like the video microscope, which in some circumstances allow one to see mechanisms that are ordinarily invisible.

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