INT. J. SCI. EDUC., 1998, VOL. 20, NO. 10, 1271–1286

Expert novice similarities and instruction using analogies

John J. Clement, School of Education, University of Massachusetts, Amherst, USA

Evidence is presented indicating that spontaneously generated analogies can play a significant role in expert problem solving. Since not all analogies are valid, it is important for the subject to have a way to evaluate their validity. In particular, this paper focuses on an evaluation strategy called bridging that has been observed in solutions to both science and mathematics problems. Spontaneous analogies have also been documented in the problem solving of students. The shared natural use of analogies for unfamiliar problems is an expert-novice similarity.

Some of the strategies observed in experts were incorporated in a teaching technique for dealing with students' preconceptions in mechanics. Students taught via these units achieved large gain differences over control groups. Thus non-deductive reasoning strategies used by experts can give us valuable clues concerning instructional strategies for science students. This complements the prior focus in the literature on expert novice differences with a focus on expert novice similarities.

Introduction

The documentation of differences in the reasoning of experts and novices was an important early contribution to the field of cognition in science learning. For example, studies of physics problem solving provided evidence that novices are more likely to attend to surface features in problems and to solve them by working backwards through a chain of memorized formulas, and less likely to have hierarchically structured knowledge based on abstract principles, or to solve problems by starting from explanatory qualitative principles (Chi *et al.* 1981, Larkin 1983). These findings helped inform curriculum developers of the need to move students beyond a formula-centered approach to problem-solving towards an approach that is based on understanding problems initially in terms of qualitative principles.

The present study pursues a different but complementary emphasis on expert novice *similarities* in the area of analogical reasoning processes. The role of analogies in instruction has been studied by several authors such as diSessa (1983), Johsua and Dupin (1987), Thiele and Treagust (1991), and Glynn and Duit (1995), to name a few. Studies of this kind are still relatively rare, however, and more work is badly needed. The point of departure for this study comes from our previous studies documenting the ability of both experts (Clement 1981) and beginning students to generate spontaneous analogies. Clement (1988) described 31 spontaneous analogies produced by ten scientifically trained experts while solving an unfamiliar physics problem, seven of whom generated at least one analogy. Fifty-nine analogies were observed in a second study of 16 engineering majors solving a set of different problems early in their freshman year (Clement 1987).

0950–0693/98 $12·00

Eleven of these students generated at least one clearly articulated analogy. Since it is presumably more difficult to generate analogies than it is to follow and consider an analogy generated by someone else, the latter study provided some initial encouragement that many students might be able to process and take advantage of analogies used in instruction. The studies suggested that for many of these subjects, analogy is a natural form of reasoning in both experts and students.

If the process of deciding whether an analogy is likely to be valid is crucial for using it insightfully and productively, it may be an important learning skill. Unfortunately, very little is known about how experts do this. The purpose of the first part of this article is not to project the frequency of analogy use from a sample to a population, but to explore some of the methods experts use to reason by analogy and especially to evaluate analogies. I will present several case studies of individual expert problem solutions in order to form hypothesized descriptions of these methods. I will then discuss some instructional applications of these methods.

Methods experts use in reasoning by analogy

Among the existing psychological studies of analogy, most have focused on *provoked* analogies, where at least part of the analogy is presented to the subject for completion. This section, however, focuses on *spontaneous* analogies where the subject initiates the entire analogy. In successful solutions by analogy the two contexts being compared are often perceptually different but are seen to be functionally or structurally similar in some way. Such solutions can sometimes radically restructure the subject's understanding of the problem situation and are most useful in unfamiliar problems where the subject is not able to apply a familiar principle to the problem in a direct manner.

Method

Subjects were told that the purpose of the interview was to study problem-solving methods and were asked to think aloud as much as possible during their solution attempt. All were advanced doctoral students or professors in technical fields. By 'expert problem solver' in this context, I mean a person who is an experienced problem solver in a technical field. Subjects were given instructions to solve the problems 'in any way that you can', and were asked to give a rough estimate of confidence in their answer. Probing by the interviewer was kept to a minimum, usually consisting of a reminder to keep talking. Occasionally the interviewer would ask for clarification of an ambiguous report.

Example of an analogy and a definition

Subjects were asked to solve problems such as the 'Wheel Problem' shown in figure 1. This is a question about whether one can exert a more effective uphill force *parallel to the slope* at the top of the wheel vs. at the level of the axle (as in pushing forward on the wheel of a covered wagon, for example). The correct answer to the wheel problem is that it will take less force to push at the top of the wheel.

WHEEL PUSH OR "SYSIPHUS" PROBLEM

YOU ARE GIVEN THE TASK OF ROLLING A HEAVY WHEEL UP A HILL. DOES IT TAKE MORE, LESS, OR THE SAME AMOUNT OF FORCE TO ROLL THE WHEEL WHEN YOU PUSH AT X, RATHER THAN AT Y?

ASSUME THAT YOU APPLY A FORCE PARALLEL TO THE SLOPE AT ONE OF THE TWO POINTS SHOWN, AND THAT THERE ARE NO PROBLEMS WITH POSITIONING OR GRIPPING THE WHEEL. ASSUME THAT THE WHEEL CAN BE ROLLED WITHOUT SLIPPING BY PUSHING IT AT EITHER POINT.

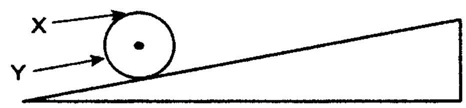

Figure 1.

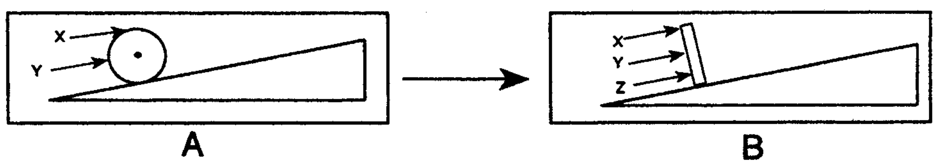

Figure 2.

As an example of a spontaneous analogy, subject S1 compared the wheel to the analogous case of pushing on a heavy lever hinged to the hill (figure 2A). He reasoned that pushing at the point higher up on the lever would also require less force. He then made an inference that the wheel would be easier to push at the top (the correct answer). Apparently he used the lever to think about what was happening in the wheel. This is an example of a spontaneous analogy, defined as occurring when the subject spontaneously shifts attention to a different situation, B, that he or she believes may be structurally similar to the original problem situation A.[1]

Subprocesses in analogy use

The solutions collected were up to 90 minutes long. Subjects indicated varying degrees of certainty about their understanding of each proposed analogous case. Sometimes they would decide that the new case was not analogous to the original problem in a useful way. In other instances further work would lead them to establish confidence in the validity of an analogy. These observations suggest that the following processes are involved in making a confident inference from a spontaneous analogy (Clement 1982). (In this description we make a distinction between the *analogous case*, shown as 'B' in Figure 2, and the *analogy relation*, represented by the arrow between A and B.)

1. *Generating the analogy*. A representation of a situation B that is potentially analogous to A is accessed in memory or constructed. A tentative analogy relation is then present between A and B (e.g. between the wheel and the lever).
2. *Evaluating the analogy relation*. The validity of the analogy relation between A and B is examined critically and is established at a high level of confidence (e.g. confidence that the wheel works like the lever).
3. *Understanding the analogous case*. The subject examines and, if necessary, develops his or her understanding of the analogous case B, so that the behaviour of the analogous case is well-understood, or at least predictable (e.g. the lever is well-understood).
4. *Transferring findings*. The subject transfers conclusions, principles, or methods from B back to A.

Steps 2, 3 and 4 above can occur in different orders in different solutions. See Clement (1991) for other case studies supporting this view of top level analogical reasoning processes.

Methods for evaluating the analogy relation

Expert methods for generating spontaneous analogies (step 1 above), are discussed in Clement (1988). The remainder of this section focuses on the methods subjects use to evaluate the validity of an analogy relation (step 2 above). The main purpose of my account here is to document a set of examples of the phenomena of analogy evaluation and to develop initial constructs and hypotheses for describing the underlying processes. Three methods will be discussed: matching key relationships; generating a bridging case; and using a conserving transformation. This paper concentrates most on the second method, generating a bridging case, and its applications to instruction.

Matching key relationships: One possible strategy for evaluating the validity of an analogy relation is to assess whether there is a structural match between key relationships in cases A and B in terms of key features that are important for the behaviour of the systems. This involves isolating the key features (including higher order relationships) in each of the cases A and B and comparing them explicitly (Gentner 1983). In the 'Wheel Problem' discussed earlier subject S1 was confident that it would be easiest to move the heavy lever in figure 2B by pushing at point X, but he questioned whether there was a valid analogy relation between the wheel and the lever. Can one really view the wheel as a lever, given that the 'fulcrum' at the bottom of the wheel is always moving and never fixed? In matching key features, he found a potential mismatch between the stationary fulcrum in the bottom of the lever and the moving fulcrum in the point of contact of the wheel that initially led him to doubt the analogy. This example illustrates how *matching key relationships* can be one method for evaluating the validity of analogies.

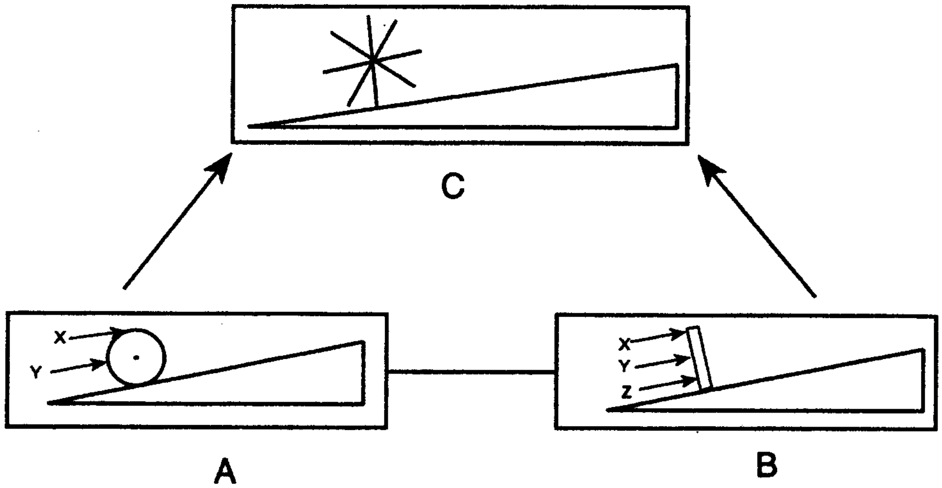

Figure 3.

Bridging: However, he also used a second, more creative method for evaluating validity. He considered a ***bridging case*** in the form of the spoked wheel without a rim shown in figure 3C. The spoked wheel allows one to view the original wheel as a collection of many levers. It is a bridge in the sense of being an intermediate case which shares features with both the wheel and the lever (Clement 1986). The bridging case reduced the subject's concern about the moving fulcrum issue and raised the subject's confidence in the appropriateness of the lever model. The spoked wheel, then, can be seen as an example of a bridging case constructed by the subject in order to establish confidence in the validity of the lever as an analogy for the wheel.

Another subject thought of an analogy to a pulley for this problem. He first used an extreme case by tipping the plane until it was almost vertical. He then added gear teeth to the wheel and the plane. After this he claimed that the problem was beginning to 'feel like a pulley' and drew a rope going up parallel to the plane from the edge of the wheel at X. However he was worried that the analogy might not be valid because of the forces the rope would exert on the wheel along its circumference. He then generated the bridging case of a rope tied to an eyelet at point X on the wheel. This helped convince him that the wheel really would act like the pulley and that it would be easier to push at X.

Bridging from doughnuts to cylinders: Another example of a bridge occurred in a solution to the mathematics problem (shown in figure 4) of finding the volume of a doughnut. Subject S3 first conjectured that the volume might be the same as the answer to the analogous problem of finding the volume of a cylinder (the 'straightened out' doughnut). He thought the appropriate length for the cylinder would be equal to the central or 'average' circumference of the torus ($2(r_1 - r_2)$) but was only '70% sure' of this. However, he then evaluated the plausibility of this choice by considering the bridging case of a square-shaped doughnut shown in figure 5. He then showed that the four sides of the square doughnut could be joined end to end to form a single long cylinder with slanted ends. He reasoned that the volume of

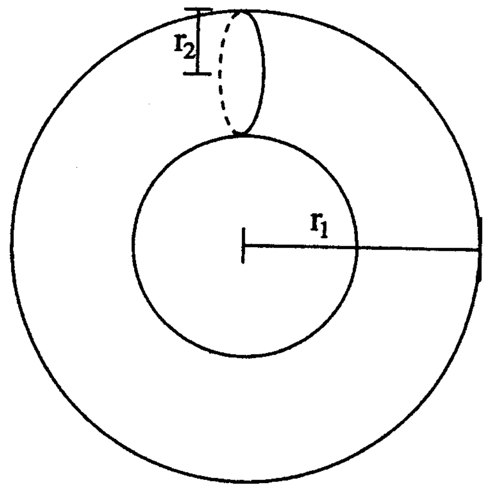

Figure 4.

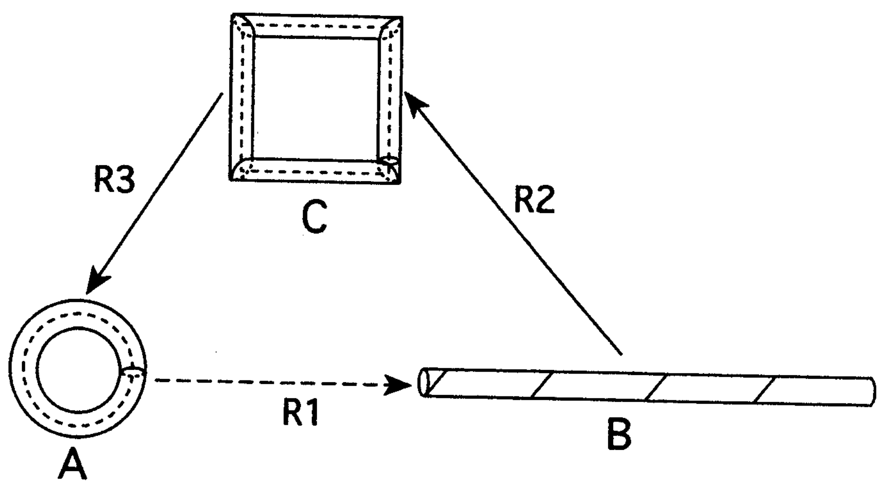

Figure 5.

this long cylinder would be exactly equal to its circular cross section times its central length and that therefore the appropriate length to use in the square doughnut was the average of its inner and outer perimeters. This raised his confidence in his original solution to '85%'. He then reached the same conclusion for the case of a hexagonal doughnut, and this raised his confidence to '100%' for the problem. This is an example of a multiple bridge. Thus the bridging cases of a square and hexagonal doughnut helped the subject change his original conjecture about the length of the cylinder into a firm conviction.

A bridge used by Newton: One of the most extraordinary scientific analogies of all time was propounded by Robert Hooke and Isaac Newton in the seventeenth century. They claimed that the moon falls toward the earth due to a gravitational force, just as an everyday object (such as an apple) does. To a modern physicist, this may seem more like an obvious fact than a creative analogy, but to advocate such an idea in Newton's time was not an obvious step at all. One has only to imagine the consternation that would be produced by telling someone ignorant of science that the moon is falling.

The proposed analogy relation is represented by the dotted line in figure 6. Essentially this conjecture says that the same causal mechanism of a gravitational force is involved in making the moon move and making an apple fall. A multiple bridge used by Newton to support this analogy in his *Principia* is shown in figure 6c. This is the idea of a cannonball fired faster and faster until it enters into orbit around the earth – a premonition of modern rocketry. Although we do not know whether this drawing conveys an idea that played a role in Newton's initial theorizing, at the very least he must have thought that it would help his readers to conceptualize the role of gravity in orbital motion. These bridging cases stand between the case of a cannonball dropped straight down and the case of the moon circulating in orbit. They help one perceive how the motion of a dropped object and the motion of the moon can be seen as having the same cause in the gravitational pull of the earth. Thus bridging cases are to be found in the history of science as well as in the transcripts of expert problem solvers.

In fact the presence of a series of many bridging cases here suggests the possibility of smooth transition from the vertical drop to the orbiting object. In the case of multiple bridges we are approaching what can be considered a third method of analogy evaluation, namely, finding a conserving transformation. Such a transformation changes case A into case B while conserving important relationships that make A analogous to B. Thinking about increasing the horizontal speed of launch in this case would constitute a conserving transformation since the major relationship of gravity causing the acceleration of the object toward the center of the system remains unchanged.

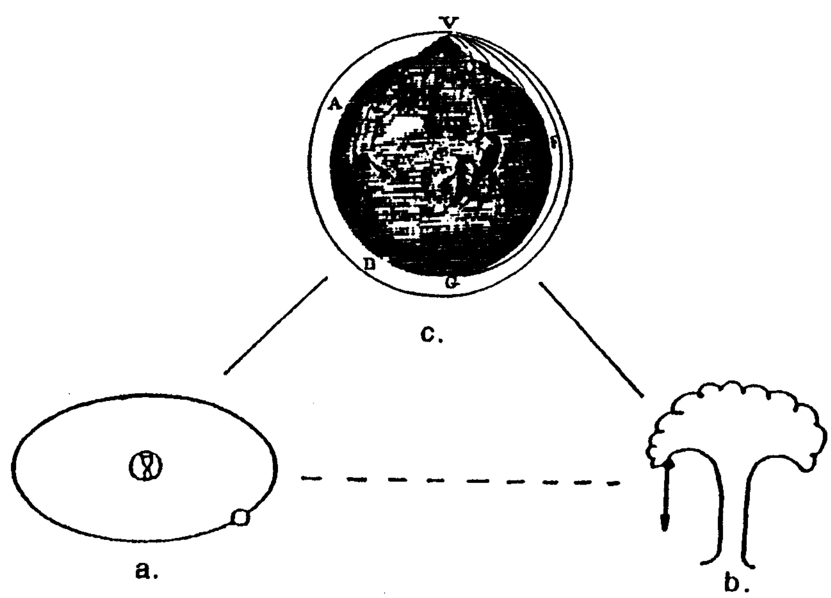

Figure 6.

Analogical reasoning in science instruction

Spontaneous generation of analogies by students

Are there expert–novice similarities in the area of analogical reasoning? As mentioned earlier, the spontaneous use of analogies has been documented not only in thinking aloud interviews with scientists (Clement, 1981, 1988), but also with students. Clement (1987) documented 59 analogies generated by college engineering majors during physics problem-solving. So from the start, we felt that expert methods of using analogies might be suggestive of instructional approaches, one of which is described in the remainder of this section.

Classroom teaching studies: use of bridging analogies and anchoring intuitions

In this section I describe a study which makes an explicit attempt to use analogies and to tap physical intuition schemas in instruction (Clement 1993). One simple but fundamental misconception observed in many physics students is that they do not believe that static objects can exert contact forces. A table cannot push up on a book, they say, it's only 'in the way', serving as a *barrier* that keeps the book from falling, but not as a force-producing object.. The physicist on the other hand, views the table as elastic – deforming a tiny amount in response to the force from the book and providing an equal and opposite force upward to keep the book from falling.

Intervention: The following technique for dealing with this difficulty was designed for use in high school physics classes. First, an '*anchoring example*' of a hand pushing down on a spring was used which draws out a physical intuition in the student that is in agreement with accepted physical theory (most students agree that the spring pushes up on the hand). Then, a chain of bridging analogies was used, as shown in figure 7.

Here an attempt is made to gradually transfer the student's intuition from the anchoring example of the hand on the spring, first to a near case of the book on a foam pad, then to the book on a thin flexible board, and finally to the book on the seemingly rigid table. It was hoped that the analogy relations linking each pair of examples in this chain are each easier to understand than the original more distant analogy between the hand on the spring and the book on the table. The teachers taught Socratically during this thirty-minute session, posing questions, summar-

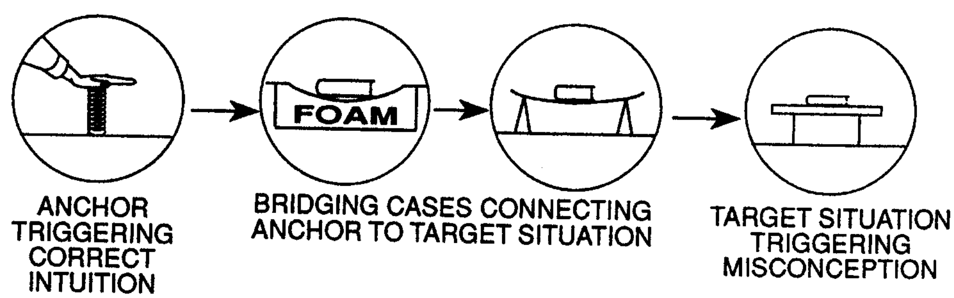

Figure 7.

izing and paraphrasing student comments, and keeping the discussion from wandering off track, but not revealing their own views. This led to some unusually animated discussions in some classes. Students were asked to compare similarities and differences between the anchor, target and bridging cases, prompting them to evaluate the analogy relations between them. Students also voted at several points on whether they believed the table was exerting a force. Towards the end of the lesson, the teacher also provided a microscopic model of solids as made up of atoms with spring-like bonds between them. (In some cases this model had already been introduced by a student during the discussion.) Following a technique used by Minstrell (1982), the teacher then performed a demonstration in which a laser beam or arc light is bounced off of a mirror lying on a table onto the wall. When the teacher stood on the table, students could see the deflection of the beam on the wall, indicating that the table was bending. Thus there were multiple approaches used to raise the 'plausibility level' of the ideas in this lesson: a chain of bridging analogies grounding the concept in an anchoring example; a visualizable microscopic model which is also grounded in the anchoring example; and an empirical demonstration supporting the deformation idea.

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. Seven lessons were designed to deal with normal forces, frictional forces, tension, and Newton's third law of action and reaction in collisions. In this article I concentrate on the normal forces lesson and results.

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 teachers in two other high schools. The experimental group consisted of 150 students while the control group contained 55 students. Experimental teachers participated in a one-week workshop on the lessons during the summer in the pilot and experimental years.

The teaching strategy described above was evaluated by giving identical pre- and post-tests to experimental and control classes. The test instrument 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 adjust or replace questions and answer choices that were not reflective of the students' conceptions. Identical pre- and post-tests were given about six months apart: in the second month of the course just before the first experimental lesson and again about two months after the final experimental lesson. Thus the retention periods measured by the post-tests were two months or more for all lessons. All teachers were blind to the problems on the tests. The above lessons were taught to experimental classes while control classes used their normal curriculum.

Results

The experimental groups achieved significantly greater gains than control groups. The gain differences were on the order of one standard deviation in size. The

Table 1. Gains for control (n = 55) vs. experimental (n = 150) classes.

(Points Possible = 6)	Static Normal Forces		
	Pre-test	*Post-test*	*Gain*
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, $p < .0001$).

results for the unit on static normal forces are shown in table 1. Similar results on lessons involving bridging strategies were also reported in the areas of friction (Control Gain: 13.9%, Experimental Gain: 40.6%, $t = 5.33$, two-tailed, $p < .0001$) and the dynamic Third Law in collisions (Control Gain: 14.5%, Experimental Gain: 44.3%, $t = 6.54$ two-tailed, $p < .0001$) (Clement 1993).

These results provide reason to be encouraged that one can obtain a measurable effect using non-formal reasoning methods in lessons designed to deal with misconceptions. In essence, the approach attempts to anchor the students' learning in the portion of their physical intuitions that is in agreement with current theory, and analogical reasoning is used to extend these intuitions to new situations. Analogical bridging is a technique that appears to help them do this in a way that makes sense to them. Nine units for dealing with students preconceptions in mechanics have been published in Camp and Clement *et al.* (1994). Research on other units showing similar gains on gravity and inertia units is described in Brown and Clement (1992).

Not every analogy works

In another study (Brown and Clement 1989) the limitations of certain analogies were explored in case studies of one-on-one tutoring interviews using anchoring analogies and bridging. One target problem used concerned two stationary skaters of equal mass facing each other: if they hold their skates straight toward each other and one skater pushes on the chest of the other, will one skater move with greater speed as they move apart? The physicist would predict equal speeds. One case study subject said that the skater being pushed would move faster, as do many other students, because, 'some of the force pushes it [the skater doing the pushing] backwards, but the majority of it is going, is going forwards'.

The more fully symmetrical situation of two equal mass carts being forced apart by a compressed spring which is not attached to either cart was an anchoring case for this student since she believed that the carts would move with equal speeds. However, she did not think this situation was analogous to the target problem. The tutor then introduced a bridging case that was the same as the anchoring situation with the carts except that the spring of negligible mass was attached to one of the carts. However this bridge did not work because the student believed that this situation would lead to unequal speeds as in the skaters problem. No longer was the push 'between them and out' it was now going 'from one side to another', in her words. Apparently, removing the symmetry of the anchoring case, even in a very small way, also removed the possibility of equal velocities for this student. Thus the anchor was 'brittle' in the sense that any small change to the anchoring situation made the useful intuition associated with it inoperative. Perhaps the anchor depends on symmetry in this case – too narrow a characteristic for developing Newton's Third Law. Apparently certain anchoring analogies do not help instructionally, even when additional bridging analogies are provided, and we must rely on teaching experiments to tell us which analogies are most productive. This again underscores the role of research in curriculum development.

Discussion

In this section I will move beyond direct inferences from the data above to formulate hypotheses concerning the successful use of analogies by experts and in instruction.

Use of Analogy

The first claim of this article is that there are expert–novice similarities in the area of analogical reasoning. Observations from classroom discussions during the lessons described above indicate that students provide evidence for the analogical reasoning processes listed in table 2 (Schultz and Clement 1994). These are processes that were documented in experts and indicate a set of expert–novice similarities that we believe have important implications for instruction. It seems likely that they point to student capabilities that have previously been insufficiently utilized in instruction. I am not claiming that novices are just as skilled as experts at using analogical reasoning. The point is that with some scaffolding and support, most students can engage in essential aspects of analogical reasoning. It is plausible that this engagement helps make learning more interactive for them.

I have focused here on expertise in the process of problem-solving, as opposed to expertise in the content area of the problem. In fact in most cases the experts were solving a problem outside of their area of content expertise. Of course we find big expert–novice differences when we look at experts' knowledge of content in their own area. Sometimes such expert solutions are rather uninteresting because they can involve routine algorithms or stylized applications of knowledge that has become routinized. But the important point is that we find some expert–novice similarities when we shift the focus from expert knowledge to expert reasoning.

The instructional approach emphasized using not just analogies, but 'anchoring analogies' – those that relate to ideas for which we have empirical evidence that a large number of students believe them with reasonable confidence. By drawing on research that looks for anchoring analogies (Clement *et al.* 1989), the instructor tries to ensure that the ideas are intuitively strong in the sense of being self-evaluated. Even when an anchor has been found, the teacher must also obtain enough feedback from students to ascertain that the anchor is not 'brittle' in the sense described above. An hypothesis that should be tested further is that using such anchoring ideas in instruction leads to a more flexible model and greater retention.

Table 2. Analogical reasoning processes indicated in evidence from classroom discussions.

—Generating analogies spontaneously;
—Tapping intuitions that give them confidence in their predictions for anchoring analogies (that can then be used as a secure basis for model building);
—Evaluating analogies (the initiative to do this in these lessons is sometimes prompted by the teacher);
—Occasionally generating bridging analogies (e.g. after seeing the book on the table problem and the anchor of the hand pushing on the spring, one student proposed the example of a table made out of thin cardboard);

Evaluating the analogy relation

In regard to the second item on the list of similarities in table 2, it was found that experts allocate considerable energy to evaluating the validity of an analogy. They often spend significant amounts of time on this before moving ahead with an analogy. This behaviour contrasts somewhat with a common view of the role of analogy in instruction. Analogies are viewed as a *shortcut* for saving time in instruction because they are thought to introduce a whole system of relationships in one step. However we have found that in areas of science where misconceptions are prevalent, it can take a considerable period of time for students to reflect on and comprehend an analogy that implies a significant conceptual change. And Clement (1989) found that although students have been observed to criticize and evaluate their own analogies spontaneously, this behaviour is less common in students working alone than it is in experts. Therefore this process may need to be supported during instruction. Schultz and Clement (1994) present a transcript from a physics classroom showing that, under the right conditions, students in a group can criticize each other's analogies, and even generate bridging analogies, so group discussion may provide some of this support.

Thus analogies are not always a 'quick fix' to the problems of instruction, even though they may be more efficient than other methods. The problem is that in many cases we have underestimated the size of the conceptual problem and the time needed to deal with it. The 'quick fix' view does not take into account the need for students to evaluate an analogy – to ask themselves and discuss whether it makes sense to believe them. The present author views this as crucial for deep understanding.

This emphasis on analogy evaluation also highlights one of the senses in which this is a constructivist teaching method. Students also bring familiar and sometimes creative examples of their own into discussions, and the teacher is very careful not to dismiss these. Although the teachers introduce key target and anchoring examples into the discussion, they do *not* reveal their opinion on whether the anchor is analogous to the target problem for a considerable period of time. 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.

Hypotheses about the nature of bridging analogies

In this section I propose two different cognitive hypotheses for how bridging works to support a process of conceptual change.

1. Bridging was cited as one method for evaluating analogies. One hypothesis for why the bridging method is effective is that it is easier to evaluate a 'close' analogy than a 'distant' one. The bridge divides the analogy into two small steps which are easier to evaluate than one large step. It is easier to see that the real wheel should behave like a rimless spoked wheel, and that the rimless spoked wheel should behave like a lever, than to make this inference in one step. Thus a bridging case may divide the problem of evaluating an analogy into two smaller problems (evaluating two 'closer' analogies). Here the emphasis is on evaluating the similarity of two structures.
2. Bridging may gradually extend the general idea of elastic force from anchor to bridge to target: providing a guide for applying and adapting a perceptual motor schema to new situations. Here the emphasis is on the gradual adaptation of a perceptual motor schema's capacity to generate mental simulations.

For example, returning to the case of Newton's thought experiment with the cannon, I referred to the series of bridging cases there as conserving transformations. That is because each addition of a bit more powder to the charge in the cannon stretches the application of the 'gravity causing falling toward the center' schema a little further. Thus in this view it may be a series of conserving transformations that aid in the gradual expansion of the domain of applicability of an intuitive conception.

In the case of instruction, an analogy must make sense to the student for it to do any good. What it means for an analogy to 'make sense' is a deep question. Hypothesis two says that it involves extending the domain in which students can apply conceptions via mental simulations (Clement 1994). For example, students extend their intuitions about the dynamic properties of springs to apply to initially unrelated objects like tables. In doing so they project the action-imagery of deformation and reaction forces into seemingly static and passive objects like the table. The spring serves here as the paradigmatic case for the general model of an elastic force. New cases that are seen as 'acting like' (analogous to) a spring are added to the model's domain of applicability. The idea of bridging brings order to this process in allowing for the gradual expansion of the elastic force model and its domain of applicability. If this is true, bridging as a teaching technique many share more with coaching than with lecturing; students must learn to construct this kind of action imagery for themselves in order for it to 'make sense'. As they try to do this and talk about it, the teacher can coach the process by suggesting the next most difficult example to attempt. The relevance of the coaching metaphor here can be seen in the example of a tennis coach having a student learn by doing ground strokes at first, and then extending and building on this skill to handle volleys. Here part of the work is a gradual process of adjustment of perception (or imagery) and action, and in this view this is part of what is needed in the case of schema adaptation in physics learning.

As in the case of experts, because they can be employed without the use of mathematical symbols, the bridging cases used here appear to be based on knowledge representations that are qualitative physical intuition schemas, not at a level that uses formal notations. Bridging is not always essential for analogy use, as there are other processes for evaluating analogies. But bridging may be an important tool for stretching the domain of applicability of an anchoring intuition to a new situation, i.e. for making the intuition more general and powerful. In this view analogies and bridging are 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 at this level that make sense to students.

In this regard Brown and Clement (1992) conducted a study in which high school chemistry students who had not had physics were asked to 'learn aloud' individually as they worked through a textual presentation of the bridging analogies strategy for the book on the table lesson. Students taught with this method had significantly higher pre-post gains than students in a control group. One of the retrospective comments by students that supports the latter view of the source of effectiveness of bridging is the following:

> Out of context you just compare the spring and the table – it wouldn't help. But you sort of built a way up from the spring, which is obvious, to a flexible board, to a not so flexible board, to foam rubber, to a table, which is pretty good.

This quotation is consistent with an 'extending the domain of application of a "springiness" schema' view of the role of bridging cases here.

The control group in this case read a passage of equivalent length from a well-known physics text book which presented many concrete examples after stating Newton's Third Law. This passage focused on citing many examples rather than developing analogy relations and models with a few carefully selected examples. It was as if the control text were aiming to have the student reinforce or induce a very general principle from a large set of unordered examples. In contrast, the superior performance of the experimental group argues that the development of analogy relations between those examples in order to develop a mechanistic model may be very important.

Further applications to instruction

A similar theme is recommended on a larger scale in a larger set of lessons for teachers (Camp *et al.* 1992) that includes the lessons discussed in this article. The conception of elastic reaction forces, starting from normal forces in the book on the table case, is carefully extended to friction, collisions and tension. Later, force pairs are introduced for magnetism and gravity, and all of these are eventually used as examples of Newton's Third Law. Thus the book works gradually toward the general Third Law via the gradual expansion and modification of the student's initial intuitions. This is a very different programme than starting from the announcement of the general Third Law, and then applying it to various examples (as did the control text in Brown's experiment). We believe that in the former case, there may be an enhanced development of expanded physical intuition and sense-making that helps explain the fact that the units described here have led to large gains over control groups, as described earlier.

The two hypotheses proposed above concerning the nature of bridging as a process should be evaluated in further research providing more evidence on whether one or both are valid. It is not always possible to find helpful analogies or bridges for a given topic and therefore these should not be considered to be universally applicable methods. However, they were used in seven of the nine units in the curriculum described above, and it is probable that the full potential for analogy use in instruction has not been fully exploited in other areas.

Other topics may require successive cycles of mental model development that may utilize more than one anchoring analogy (Spiro *et al.* 1989, Steinberg and Clement 1997.) This is another important topic for future investigation.

Conclusion

Non-deductive strategies like generating analogies can be powerful tools in the hands of expert scientists. The fact that experts use analogical reasoning processes supports the idea that they are not a trivial form of reasoning and that they can be important in learning science. Not only generating, but *evaluating the validity of* analogies appears to play a very important role in expert problem solutions.

The method of bridging analogies, as an evaluation method used by expert scientists as well as by Newton, appears to be a promising strategy for helping students overcome misconceptions in science. This strategy illustrates how non-deductive reasoning strategies used by experts can give us valuable clues concerning instructional strategies for science students. Both are capable of using analogies that depend on anchoring intuitions and both seem to comprehend bridging analogies. Students appear to benefit from working on confirming the validity of an analogy relation. These findings complement the prior focus in the literature on expert novice differences with a focus on expert novice similarities.

Notes

1. The following observation criteria were used in Clement (1988) to code for the generation of a *spontaneous analogy:*
   1. The subject, without provocation, refers to another situation B where one or more features ordinarily assumed fixed in the original problem situation A are different, that is, the analogous case B violates a 'fixed feature' of A not ordinarily considered to be a problem variable.
   2. The subject indicates that certain structural or functional relationships (as opposed to surface features alone) may be equivalent in A and B.
   3. The related case B is described at approximately the same level of abstraction as A.

References

BROWN, D. and CLEMENT, J. (1989) Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. *Instructional Science*, 18, 237–261.

BROWN, D. and CLEMENT, J. (1992) Classroom teaching experiments in mechanics. In R. Duit, F. Goldberg and H. Niedderer (eds), *Research in Physics Learning: Theoretical Issues and Empirical Studies* (San Diego, CA: San Diego State University).

CAMP, C., CLEMENT, J., BROWN, D., GONZALEZ, K., KUDUKEY, J., MINSTRELL, J., SCHULTZ, K., STEINBERG, M., VENEMAN, V. and ZIETSMAN, A. (1994) *Preconceptions in Mechanics: Lessons Designed to Deal with Student's Conceptual Difficulties* (Dubuque: Kendall-Hunt).

CHI, M. T. H., FELTOVICH, P. and GLASER, R. (1981) Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121.

CLEMENT, J. (1981) Analogy generation in scientific problem solving. *Proceedings of the Third Annual Conference of the Cognitive Science Society*, Berkeley 1981 (Hillsdale, NJ: Erlbaum).

CLEMENT, J. (1982) Analogical reasoning patterns in expert problem solving. *Proceedings of the Fourth Annual Meeting of the Cognitive Science Society*, Ann Arbor, Michigan (Hillsdale, NJ: Erlbaum), 79-81.

CLEMENT, J. (1986) Methods for evaluating the validity of hypothesized analogies. *Proceedings of the Eighth Annual Meeting of the Cognitive Science Society* (Hillsdale, NJ: Erlbaum).

CLEMENT, J. (1988) Observed methods for generating analogies in scientific problem solving. *Cognitive Science*, 12, 563–586.

CLEMENT, J. (1989) Generation of spontaneous analogies by students solving science problems. In D. Topping, D. Crowell and V. Kobayashi (eds), *Thinking Across Cultures: Third International Conference* (Hillsdale, NJ: Erlbaum).

CLEMENT, J. (1991) Non-formal reasoning in science: The use of analogies, extreme cases, and physical intuition. In J. Voss, D. Perkinsand J. Segal (eds), *Informal Reasoning and Education* (Hillsdale, NJ: Erlbaum).

CLEMENT, J. (1993) Using analogies to deal with students' preconceptions in physics. *Journal of Research in Science Teaching*, 30, 10, 1241–1257.

CLEMENT, J. (1994). Use of physical intuition and imagistic simulation in expert problem solving. D. Tirosh (ed.), *Implicit and Explicit Knowledge* (Norwood, NJ: Ablex).

CLEMENT, J., BROWN, D., AND ZIETSMAN, A. (1989) Not all preconceptions are misconceptions: Finding anchoring conceptions for grounding instruction on students' intuitions. *International Journal of Science Education*, 11, 554–565.

DISESSA, A. A. (1983) Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens (eds), *Mental Models* (Hillsdale, NJ: Erlbaum).

GENTNER, D. (1983) Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7, 155–170.

GLYNN, S. M. and DUIT, R. (1995) Learning science meaningfully: Constructing conceptual models. In S. M. Glynn and R. Duit (eds), *Learning Science in the Schools* (Mahwah, NJ: Erlbaum), 3–33.

JOHSUA, S. and DUPIN, J. (1987) Taking into account student conceptions in an instructional strategy: An example in physics. *Cognition and Instruction*, 42, 117–135.

LARKIN, J. H. (1983) The role of problem representation in physics. In D. Gentner and A. L. Stevens (eds), *Mental Models* (Hillsdale, NJ: Erlbaum).

MINSTRELL, J. (1982) Explaining the 'at rest' condition of an object. *Physics Teacher*, 20, 10–14.

SCHULTZ, K. and CLEMENT, J. (1994) The use of class discussion and analogies in teaching: Examples from a physics classroom. Appendix in C. Camp, J. Clement, J., D. Brown, K. Gonzalez, J. Kudukey, J. Minstrell, K. Schultz, M. Steinberg, V. Veneman and A. Zietsman, *Preconceptions in Mechanics: Lessons Designed to Deal with Student's Conceptual Difficulties* (Dubuque: Kendall-Hunt).

SPIRO, R., FELTOVICH, P. J., COULSON, R. L. and ANDERSON, D. K. (1989) Multiple analogies for complex concepts: Antidotes for analogy-induced misconception in advanced knowledge acquisition. In S. Vosniadou and A. Ortony (eds), *Similarity and Analogical Reasoning* (Cambridge: Cambridge University Press), 499–531.

STEINBERG, M. and CLEMENT, J. (1997) Constructive model evolution in the study of electric circuits. In *Proceedings of the International Conference From Misconceptions to Constructed Understanding* (Ithaca: Cornell University Press).

THIELE, R. and TREAGUST, D. (1991) Using analogies in secondary chemistry teaching. *Australian Science Teachers Journal*, 37, 10–14.