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Overcoming misconceptions via analogical reasoning: abstract transfer versus explanatory model construction

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Abstract. In most work investigating factors influencing the success of analogies in instruction, an underlying assumption is that students have little or no knowledge of the target situation (the situation to be explained by analogy). It is interesting to ask what influences the success of analogies when students believe they understand the target situation. If this understanding is not normative, instruction must aim at conceptual change rather than simply conceptual growth. Through the analysis of four case studies of tutoring interviews (two of which achieved some noticeable conceptual change and two of which did not) we propose a preliminary list of factors important for success in overcoming misconceptions via analogical reasoning. First, there must be a usable anchoring conception. Second, the analogical connection between an anchoring example and the target situation may need to be developed explicitly through processes such as the use of intermediate, "bridging" analogies. Third, it may be necessary to engage the student in a *process* of analogical reasoning in an interactive teaching environment, rather than simply presenting the analogy in a text or lecture. Finally, the result of this process may need to be more than analogical transfer of abstract relational structure. The analogies may need to be used to *enrich* the target situation, leading to the student's construction of a new explanatory model.

Introduction

Students' prior knowledge has been increasingly recognized as playing a crucial role in learning. According to this view, prior knowledge determines the meanings derived from instruction, and teaching which does not build on existing knowledge and understanding will fail to produce meaningful learning. The use of analogy is often viewed as one of the primary means of drawing on students' existing knowledge. By activating relevant prior knowledge which is already understood by the learner, the analogy helps give meaning to incoming information (Royer and Cable, 1975, 1976; Mayer, 1983, 1989; Simons, 1984; Stepich and Newby, 1988).

In a traditional use of analogy in instruction, the analogy is presented to the student through a lecture or textbook passage. (The situation to be explained by analogy is called the target, and the supposedly better understood analogous situation is called the base.) When the base situation is presented, points of correspondence are drawn between elements in the base and elements in the target, unless these points of correspondence are considered obvious. As Gentner (1983) points out, these "elements" that are put into correspondence are the objects in the base and target and the relations between these objects. The features of the objects (e.g. a *wooden* table or a *metal* wire) and even that the object is a table or a wire, generally do not carry over in the correspondence or "mapping". In this view, what is similar between the base and the target is the abstract relational structure between objects. There are several assumptions inherent in such a traditional use of analogy which include the following:

1) The student has little knowledge or understanding of the target situation and would welcome a comparison to a more familiar situation.
2) The base situation is understood by the student.
3) The student accepts that the analogy is sound, either because he recognizes the aptness of the analogy, or because he accepts the authority of the teacher or text that the analogy is apt.
4) The student makes (or is helped to make) the correct correspondences between the elements in the base situation and those in the target situation.
5) An expert would view the analogy as sound. That is, the elements that are similar (to an expert) outweigh in importance the elements that are dissimilar.
6) The student is motivated to attend to the comparison.
7) The outcome of consideration of the analogy is conceptual growth, that is, new knowledge and understanding of the target where there was little before.

In this paper, we would like to examine the use of analogies when the student believes that she already understands the target situation, yet this "understanding" constitutes a misconception from the expert's perspective. We use the term "misconception" here to refer to students' ideas which are incompatible with the scientific theory being taught. To be sure, these conceptions should be respected as creative constructions of the individual. In some cases these conceptions are also adaptive and successful for dealing with the practical world. They do, however, present significant barriers to learning a subject like Newtonian mechanics and as such need to be addressed as difficulties from the perspective of the content domain being taught. As a result of such misconceptions, students may reject the aptness of potentially helpful analogies.

Using analogical reasoning to overcome misconceptions

Within the past decade and a half there has been an increasing awareness of the *detrimental* effects (to school learning) of some of students' prior knowledge. Students come to class with preconceptions which inhibit the acquisition of content knowledge and are often quite resistant to remediation (for reviews of research on students' alternative conceptions, see Driver and Easley, 1978; Driver and Erickson, 1983; McDermott, 1984; Duit, 1987). Awareness of these preconceptions has prompted a number of instructional research efforts including ours at the University of Massachusetts.

For several years we have been testing an analogical teaching strategy which attempts to build on students' existing valid physical intuitions. It is perhaps confusing that we are attempting to *build* on students conceptions in order to *change* their conceptions. However, it is our experience that students have both useful and detrimental intuitive conceptions (from the perspective of the scientific theory being taught). In this analogical instruction, we intend to increase the range of application of the useful intuitions and decrease the range of application of the detrimental intuitions. Such instruction does appear, at times, to lead to conceptual change starting from existing conceptions in that the student can make intuitive sense of aspects of the scientific theory when they were counterintuitive before. See Clement, Brown and Zietsman (in press) for further discussion of such valid, "anchoring" intuitions.

By establishing analogical connections between situations students initially view as not analogous, students may be able to extend their valid intuitions to initially troublesome target situations. This strategy, called the "bridging strategy," has been used in tutoring, computer tutoring and classroom instruction, with some apparent success (Clement and Brown, 1984; Brown, 1987; Brown and Clement, 1987b; Clement *et al.*, 1987; Murray, Schultz, Brown and Clement, in press). In this paper, we examine four case studies of students tutored with this strategy. Based on an analysis of the case studies we propose a preliminary list of factors important for conceptual change via analogical reasoning. The strategy is described below.

Bridging strategy

The first step in the bridging strategy is to make the misconception explicit by means of a target question. For example, a question which draws out a misconception for a majority of introductory physics students concerns the existence of an upward force on a book resting on a table. Students typically view the table as passive and unable to exert an upward force. The next step is to suggest a case which the instructor views as analogous (such as a hand holding up a book) which will appeal to the student's intuitions. We call such a situation an anchoring example (or, more briefly, an anchor). However, even though the student may reason appropriately about the anchoring example, she may still be unconvinced of a valid analogy relation to the target case.

When this occurs the instructor attempts to establish the analogy relation. In this case the instructor first asks the student to make an explicit comparison between the anchor and the target. If the student still does not accept the analogy relation, the instructor then attempts to find a "bridging analogy" (or series of bridging analogies) conceptually intermediate between the target and the anchor. This can often be done by transforming the anchor to make it conceptually closer to the target.

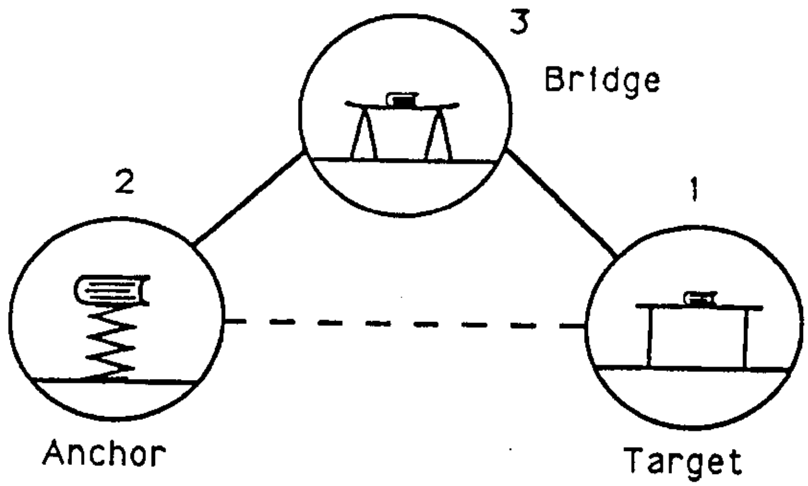

Figure 1. Analogy diagram for hypothetical bridging example. Dotted lines indicate initial rejection of analogy relation, solid lines indicate initial acceptance of analogy relation.

Hypothetical example

As an example of bridging, consider the following hypothetical interaction, illustrated in Figure 1. (Although fictitious, the interaction is not unlike those reported in Brown, 1987.) The numbers in Figure 1 refer to the nodes in the diagram, which represent the situations considered by the student.

1) *Book on a table.* In response to a question about the forces acting on a book at rest on a table, the student indicates that the table is not exerting an upward force on the book. (The physicist would say that the table is exerting an upward force on the book balancing the downward force of gravity).

2) *Book on a spring.* As a potential analogy, the interviewer asks the student to consider the situation of a book resting on a spring. In this case the student indicates that the spring would be exerting an upward force since the spring is compressed and "wants" to return to its original position. However, he rejects the analogy relation to the case of the book resting on the table, since the table is rigid and does not need to return to its original position.

3) *Book on a flexible table.* At this point the interviewer introduces the situation of a book resting on a flexible table (e.g. a flexible board between two supports). Upon reflection the student accepts that this situation is analogous to the book on the spring situation, since in both situations there is compression or bending and accompanying "desire" to return to an equilibrium position. He also accepts that the situation of the book on the flexible board is analogous to the situation of the book on the table since the table can be viewed as a thick board which would still bend, although imperceptibly.

One way to interpret the beneficial effects of this process is in terms of analogical transfer achieved by using intermediate bridging cases. In other words, bridging is helpful because it establishes an analogical connection in the student's mind which was rejected before. However, in the discussion section we will hypothesize how the use of "explanatory models" can go beyond analogical transfer.

Case studies

In this paper we examine case studies of four interviews with three students involving four different misconceptions in which this bridging strategy was employed. Two of these interviews achieved some noticeable conceptual change and two did not. Often, interventions which fail to achieve the instructional objectives are as illuminating as sessions which achieve the objectives. Set against the background of successful attempts, failed attempts can serve to highlight those factors important to success.

Method

Although these interviews could be called tutoring interviews, the students were informed that the interviewer would take a "devil's advocate" stance in order to foster discussion. In this way students were encouraged to adopt only those ideas that seemed reasonable to them, as they would be unsure whether the arguments the interviewer was advancing were "correct" or simply made to encourage discussion. Two of the three students were high school juniors currently taking chemistry, who had not yet taken physics, and one was a freshman at the University of Massachusetts who had not taken physics in high school or college. The interviews were conducted by David Brown.

Case 1

In this interview, Mark (names used are not the students' real names) considered the question of whether a table exerts an upward force on a book resting on the table. The following numbered sections correspond to the numbered nodes in the diagram in Figure 2. Although this interview dealt with the same target problem as the hypothetical case above, many more potential analogies were introduced and discussed. Some of these are examples of what could be called "sub-bridges," that is, situations which are intermediate between two situations, at least one of which is not the original anchor or target. For example, node 5 is a bridge between two situations neither of which is the original anchor or target. (Mark was a freshman at the University of Massachusetts who had not taken physics in high school or college.)

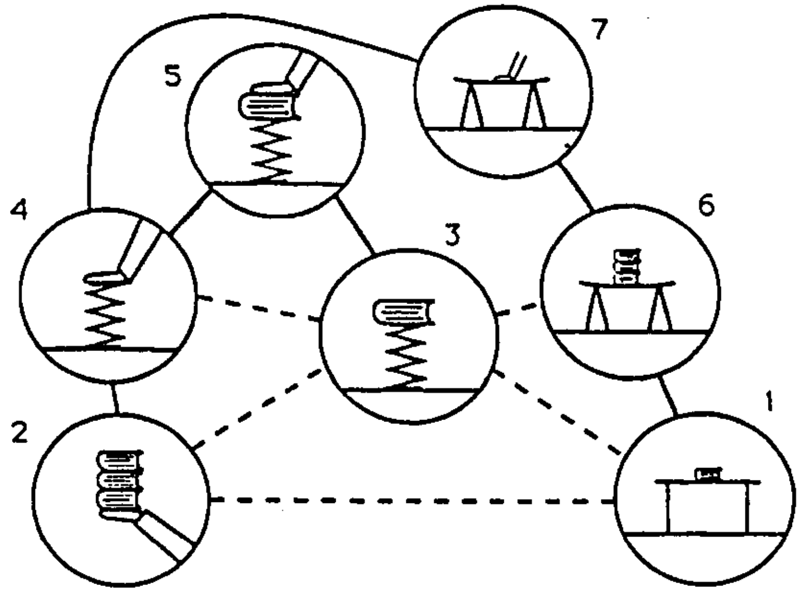

Figure 2. Analogy diagram for Case 1

1) *Book on the table.* The target question asked whether a table exerts an upward force on a book resting on the table. In response to this question, Mark replied (numbers indicate placement in the transcript):

042 S: No, it's just, it's just, ah, a barrier between the floor and the, um, the position the book is at right now.

2) *Books on the hand.* Although he said the table would not exert an upward force, he indicated he would definitely have to exert a force upward in the case of several books resting on his hand. However, he did not view these situations as analogous (book on the table and books on the hand). When asked why he answered differently in the two situations, he replied that his arm has muscles.

3) *Book on a spring.* The first bridging analogy introduced was that of a book resting on a spring (S stands for student, I for interviewer).

070 S: Ah, the book is on the spring and um, this spring is absorbing, ah, the force caused by the mass of the book and the gravity. But I wouldn't say that the spring is, ah, pushing up on the book. That's just my sense.

071 I: Uh huh.

072 S: The spring itself doesn't initiate any movement.

Mark apparently views the spring as a passive entity, one that can absorb force but cannot "initiate any movement" itself.

073 I: What's the difference then between the book on the spring and the book on the hand?

074 S: Uh, muscles in the arm.

075 I: And the spring doesn't have any muscles?

076 S: Right. The spring is just, ah, a piece of metal and it'll absorb, ah, as much as it can until the point where it's completely contracted and then it will probably, ah, not absorb more energy.

4) *Hand on a spring.* The interviewer proposed a hand pressing down on a spring as a bridge between the books on the hand and the book on the spring. Mark believed that the spring would push up against his hand. However, he viewed the book versus the hand on the spring as not analogous. When asked why, he replied:

088 S: Ah, because the force, ah, being exerted on the spring by the book is only the mass of the book and the gravity. But the, ah, the force of the hand, um, could be all kinds of, is you know, your muscles, the muscles in your hand.

5) *Hand on a book on a spring.* As a bridge between the hand on the spring and the book on the spring, the interviewer suggested a hand pressing down on a book on a spring. Mark said the spring would definitely be pushing up against the book in this case. When asked to compare this to the situation of the book resting on the spring, he responded:

106 S: Because now with your hand off of [the book] the, no downward pressure is really being exerted. Actually now I see the point you're trying to make, it's, ah, it's only the amount of force being, push being exerted on the spring is varying. It just seems to me that there's no force being exerted on the spring when the book is on there, the gravity's almost invisible, we don't even think about it. But now I realize that it, there is no difference between the two that you just asked me.

6) *Books on a flexible board.* Now that Mark believed that the spring exerts an upward force on the book, the interviewer attempted to establish the case of several books resting on a flexible board between two supports as a bridge between the book on the spring and the book on the table.

7) *Hand on a flexible board.* Initially, Mark said that the board would be simply a barrier, but then he generated his own bridge between the earlier situation of the hand on the spring and the books on the flexible board.

123 I: Would you say that this board is pushing up against the books?

124 S: Ah, no I would say the board is, ah, just a barrier between the books and the area underneath the board.

125 I: Uh huh.

126 S: I don't think the, ah, well now, now that I think about it a little more, ah, the spring, ah, this board might have some of the properties similar to the, ah, spring, because the, ah, if you push down on the middle of the, right at the point where the books are located...

127 I: Uh huh.

128 S: ... the, it would probably come back up depending on the, whether the board was flexible.

129 I: I'm assuming that it is.

130 S: Or it could break if it weren't flexible, but since it is, ah, I suppose you could say that the board is pushing up the books.

Now that Mark believed the flexible board exerted an upward force on the books, the interviewer asked him to compare this situation with the situation of the book on the table.

135 S: Uh, the board is flexible and, yeah I guess that's, that's essentially it, the board is flexible and, it, ah, it probably isn't different, um, I'm starting to realize how technically it probably isn't different, it just appears different. Ah, you know, because it's a thin board, it's flexible and you can see easier that it's, um, the board is pushing up on the books. Especially after talking about the springs previously and, uh, the table is really, ah, rigid, it doesn't appear flexible even though it is in the, ah, you know, in a really, really small microscopic, ah, sense. And, ah, so there probably, scientifically there probably is no difference, it's just a matter of, ah, numbers, you know, the board is very flexible and the table is immeasurably, ah, flexible.

Later on in this interview, Mark indicated that the idea of the table exerting an upward force made "complete sense." Thus there is some indication in this case that the bridging strategy was successful in bringing about conceptual change.

Discussion

It is interesting to note several differences between this use of analogy and a more standard approach, such as presenting an analogy in a text passage and noting the points of correspondence to the target. First, Mark felt he already understood the target situation, that the table was simply a barrier preventing the book from falling to the ground, but not exerting a force on the book. Second, as a result of this understanding, he strongly resisted accepting the aptness of several proposed analogies. Third, whereas the traditional use of analogy would involve presenting the base as an analogous situation, in this case the interviewer simply suggested situations without stating that the situations were analogous. The purpose of the interview was to engage the student in a *process* of analogical reasoning, and not simply to present an analogy. Fourth, the result of the process of analogical reasoning was to *change* rather than *add* to his existing understanding of the book on the table situation. Finally, one could argue that the result of the process was that Mark came to view the table *as springy*, and not simply *as like* a spring in that it too exerts an upward force. We will return to this last point later in the paper as an important factor in the success of the instructional approach which goes beyond merely the establishment of analogical connection.

Case 2

In this interview, Tom considered the question of whether the floor exerts a force on a shuffleboard puck sliding on the floor. The physicist would say that the floor exerts a frictional force in a direction opposite to the puck's motion which slows the puck down.

Following is a discussion of the nodes in the diagram in Figure 3. (Tom was a high school junior currently taking chemistry, but who had not yet taken physics.)

1) *Sliding shuffleboard puck.* In response to the shuffleboard puck question, Mark replied that the floor does not exert any force on the puck which affects its horizontal motion.

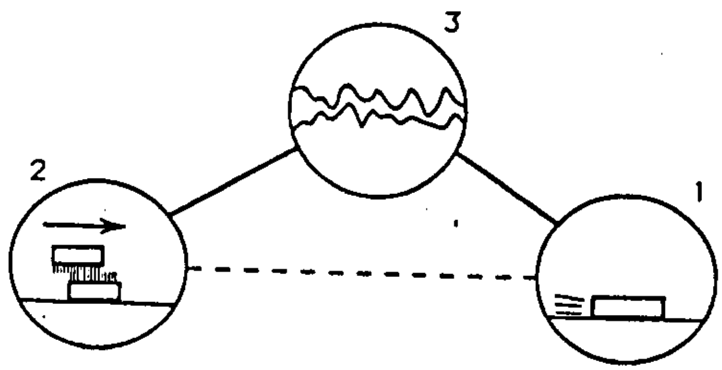

Figure 3. Analogy diagram for Case 2

2) *Intermeshed hairbrushes.* The anchor used was that of two hairbrushes slightly intermeshed, one clamped to the table and the other drawn horizontally across it to the right. Tom believed that the lower brush would exert a force to the left on the top brush. However, he did not see this as analogous to the sliding puck.

216 S: Because, the, the bottom brush is holding the top brush back, so if one is pushing to the right, the other one, the bottom one is pushing to the left.

217 I: Uh huh. Is this, um, is this situation different from the puck on the floor?

218 S: (pause)

219 I: What are you thinking?

220 S: Um, I'm thinking that, yeah it is, because the floor doesn't have, exactly have, uh, bristles like the bottom of a brush does, which are pushing against the top brush. The floor is flat.

3) *Magnified view of puck and floor.* (It is more accurate to call this situation a microscopic model rather than an analogy; the important point here is that this situation served as an intermediary between the anchor and the target.) As an intermediate situation, the interviewer asked Tom to consider a magnified view of the puck sliding in which both the floor and the lower surface of the puck would appear bumpy. After he realized that both the floor and the puck would appear "hilly and rough" (his own spontaneous description), Tom indicated that the interface of the bumpy surfaces was "the same thing" as the hair-brushes. Curiously, however, this recognition did not immediately lead to a correct answer for the sliding puck.

237 I: So is there, is there a force, um, from the floor on the puck in any direction?

238 S: I'm not sure if it's in any direction, it's, 'cause the floor isn't moving.

239 I: Uh huh.

240 S: The puck is. (Pause) I'm not really sure.

241 I: Is there a force in any particular direction in 2 [the hairbrushes], on the top brush?

242 S: I think if you move the top brush to the right, it bends the bristles.

243 I: Uh huh.

244 S: The bristles would push back to the left.

245 I: Uh huh.

246 S: And that would be a force to the left. But the floor isn't moving, but the puck is.

247 I: Uh huh. Would these bumps [in the magnified view] bend at all?

248 S: Yeah, but not as much as the bristles on the brush would.

249 I: So, would they exert some force in the other direction?

250 S: Yes, they would.

251 I: What direction?

252 S: Opposite that of the puck.

253 I: So, the puck is moving to the right, so that would be to the left?

254 S: Yes.

255 I: Uh huh. Does that make sense.

256 S: Mm hmm.

261 I: On a scale from one to ten, I'd like you to rate how much sense it makes to you that the floor exerts a force on the puck in the direction opposite to the puck's motion.

262 S: Ten...I understand that now.

Discussion

There is some indication that Tom changed his conception of the target situation. Whereas he initially believed that the floor did not exert a force on the puck affecting the puck's horizontal motion, by the end of the interview it made perfect sense to him that the floor would exert a force in a direction opposite to the puck's motion. In addition to the points of comparison with the traditional use of analogy discussed in case study one, it is again interesting to note that the result of the process was that Tom viewed the puck and the floor *as bumpy* or bristly, and not simply *as like* hairbrush bristles. (The model portrayed here is a first order model of friction – more advanced models would need to include Van der Waals forces, spot welding, etc.)

Unsuccessful attempts at bridging

The case studies described above represent relatively successful attempts to promote conceptual change by bridging between an anchoring example and a target situation by means of one or more analogies. In the following two case studies the same strategy was attempted with little apparent success.

Case 3

In this interview, Dorothy considered a target problem of two roller skaters of equal mass facing each other. One pushes on the chest of the other, forcing them apart. The physicist would say that the two skaters would both move backward with equal speeds. The nodes in Figure 4 are described below. (Dorothy was a high school junior currently taking chemistry who had not yet taken physics.)

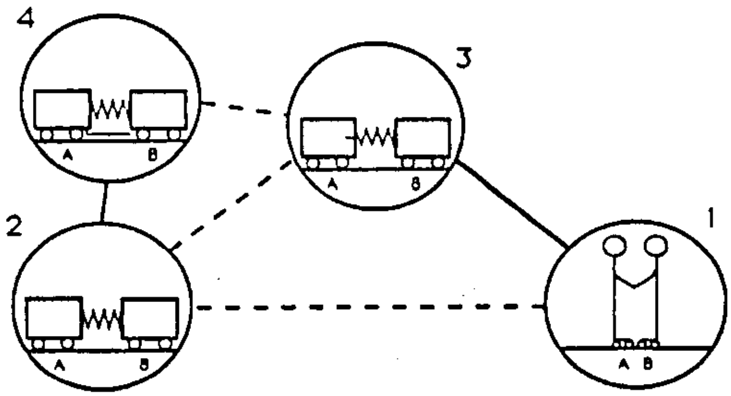

Figure 4. Analogy diagram for Case 3

1) *Skaters.* In the target problem, Dorothy indicated that the skater being pushed would move backward faster than the skater doing the pushing.

2) *Symmetrical carts.* An anchor for her was the symmetrical situation of two equal mass carts being forced apart by a compressed spring which is not attached to either cart. However, she did not view this situation as analogous to the target problem. When asked whether these situations were different, she replied:

118 S: Yeah, because um, A [the skater doing the pushing] would, A is the object that's exerting, that's exerting the force, because it has nothing pushing against it on the other side to balance the force that it's giving off. Um, some of the, some of the force pushes it backwards, but the majority of it is going, is going forwards. It's going from one side to another, more than just from between them and out, like in this situation with the carts [the symmetrical carts with the spring between them].

3) *Spring attached to one cart.* As a possible bridge, the interviewer introduced a situation almost identical to the last situation, except that in this case the spring is attached to one of the carts. Dorothy felt that this minor change would destroy the equality present in the symmetrical case.

120 S: Well, that's more similar to this, I think, to the roller skaters situation.

121 I: What would happen in that case?

122 S: Um, A [the cart with the spring attached] would move forward, would move back to the left of it, also. But B would move to the right faster.

123 I: Okay. And so, how are these situations [2 and 3] different ?

124 S: Uh well, because A is attached to this, this spring which is providing the force, um, more of the force is um, transferred onto B.

4) *Cart with platform.* As a possible bridge between the symmetric carts situation and the asymmetric carts situation, the interviewer introduced a situation in which the spring was still not attached to either cart, but after expansion the spring would drop down on a platform attached to one of the carts and be carried along with this cart. Apparently Dorothy had not been focusing on the fact that in the asymmetric situation the spring stayed with one of the carts and found this attempted bridge unconvincing.

146 S: Um, I don't think, I don't think that would make much of a difference, because at that point, any of the force that the spring was exerting has been expended on the two carts, on pushing the two carts out, so it's just a weight then.

147 I: So would they move apart at the same speed or different speeds, or...?

148 S: The same speed, I think.

Discussion

This case study provides an example of what could be called a "brittle" or "non-extendable" anchor. Although she believed strongly that the carts would separate with equal speeds in the symmetrical case, the small change of attaching the spring to one of the carts significantly altered the situation for her. No longer was the push going from "between them and out," it was now going "from one side to another." It is unclear whether this is a bridgeable chasm since any slight change to the anchor, making it asymmetric and thus analogous to the target, might, for Dorothy, make it unlike the symmetric anchor. The session ended with Dorothy still convinced the skaters would move apart at unequal speeds. (See Clement, Brown and Zietsman, in press, for a further discussion of brittle anchors.)

Case 4

The final case study is particularly interesting in that it appears anomalous. Tom (who dealt with friction above) here struggled with the idea that a moving cue ball and a stationary eight ball would exert equal forces on each other when they collide; believing instead that the cue ball would exert a greater force. This case study is anomalous in that even though Tom recognized the analogy relation between the anchor and the target, he was unwilling to accept the implication of that analogical relation. The nodes in Figure 5 are described below.

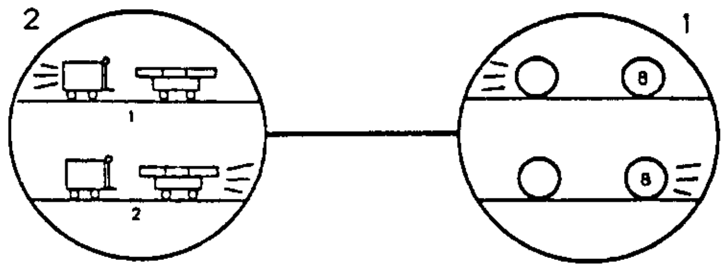

Figure 5. Analogy diagram for Case 4

1) *Colliding billiard balls.* A moving cue ball strikes a stationary eight ball. Which ball exerts the greater force, or do they exert an equal force on each other (referring to the top drawing in situation 1)?

005 S: I think because the cue ball is moving and the eight ball is stationary, that it has, it's going at a faster rate and when it strikes it has more force.

2) *Mr. T between railroad cars.* An anchor for Tom was the somewhat fanciful situation of Mr. T (a television action hero) on the front of a railroad car colliding with another railroad car carrying a large log. He believed strongly that Mr. T would feel the same force regardless of which railroad car was moving and which was stationary.

There ensued a 20 minute discussion about the relationship between these two situations (the billiard balls and Mr. T). Some excerpts from this exchange are given below.

In the first excerpt below, Tom correctly maps the base onto the target. In this correct mapping, the moving cue ball would correspond to the moving car with Mr. T on it and the stationary eight ball would correspond to the stationary log car.

021 S: I'm thinking that if the log car were the eight ball and this [the moving car with Mr. T on it] were the cue ball, that this [the moving car] would have more force. But if the log car were the eight ball and this, the second picture [log car moving and Mr. T stationary], when it strikes the cue ball the eight ball would have more force. So I'm saying that whichever one is moving at a faster rate will have the greater force.

022 I: So would Mr. T feel something different in these two situations?

023 S: No. No, I don't think he would.

In the following, Tom begins to question the mapping because of the implications.

040 I: So would the cue ball feel a different force than the eight ball feels, or would they feel the same force?

041 S: The eight ball would feel a greater force because the cue ball is moving.

042 I: So would Mr. T feel a greater force in number two then? Or would he feel the same force?

043 S: It would be the same in this. I don't think that these two [Mr. T and billiard ball situations] are the same.

When pressed, Tom appears to move into disequilibrium, unable to reject the mapping and uncomfortable with the implication of the mapping (equal forces in the billiard ball situation).

044 I: What are the differences between those two [Mr. T and billiard ball situations]?

045 S: Well in the first example he is like the cue ball going at the eight ball. And in number two [log car moving, Mr. T stationary] he's the eight ball being struck by the cue ball.

046 I: Uh huh.

047 S: (pause) I guess maybe it would be the same. (pause)

048 I: What are you thinking?

049 S: I'm thinking that in both cases, no matter what, no matter whether he's moving or the log cart is moving, he's going to get hit really hard anyway. I still can't see how that's the same as the cue ball example.

050 I: Can you say what the differences are? What's different about the two examples?

051 S: (Pause) I'm just thinking that whichever object is moving faster is going to create the most force. (pause) I'm just kind of lost.

064 I: So is this situation [Mr. T] different from the billiard ball situation?

065 S: (Pause) These two are the same, number one [Mr. T moving] and the billiard ball situation is the same. But this [Mr. T stationary], this would be like (draws) if the eight ball is moving, it hits the cue ball.

066 I: What would be, in this case here, what would happen in that situation that you've just drawn, with the eight ball moving and the cue ball [stationary]?

067 S: The eight ball would exert a greater force than the cue ball.

Interestingly, in what follows Tom regresses momentarily, resolving the disequilibrium by answering differently for the anchor situation. However, the anchoring conception is apparently too strong and he realizes that this is not a way to resolve the conflict.

072 I: So would Mr. T feel a greater force in number 2 here [when he is stationary]?

073 S: Yeah. Now I can.. yeah. (pause)

074 I: What are you thinking?

075 S: (pause) I'm thinking it doesn't really matter whether he's moving or the log cart is moving. It's not really going to matter what...(pause)

Further (failed) attempts to resolve the conflict.

085 S: It seems in this problem it would be the same – in the Mr. T problem – because it doesn't really matter whether he gets hit by the log cart or the log cart hits, or if he hits the log cart.

086 I: Uh huh.

087 S: But in this one it seems that, in the first cue ball problem, when the cue ball hits the eight ball the eight ball's going to go flying.

088 I: Uh huh. (pause) What would happen in this situation, the Mr. T situation?

089 S: When he hit the log cart, the log cart would go backwards.

090 I: Move to the right?

091 S: Yes to the right and if the log cart hit him he would go to the left. (pause)

092 I: What are you thinking?

093 S: I don't know, it's... (pause)

094 I: Are you looking at the billiard ball situation?

095 S: Mm hmm. I'm still trying to figure out why I'm saying one thing in this and I'm saying a different thing in the cue ball problem. (pause) I don't know what to say, I'm confused now.

At the end of the interview, Tom said that the unequal forces in the billiard ball situation still made perfect sense to him (a 10 on a scale from 1 to 10), that equal forces made little sense to him (a 3 on a scale from 1 to 10), and that it made perfect sense to him that Mr. T would feel equal forces in the two situations.

Discussion

It might be assumed that if the student views the anchor and the target as analogous, and the anchor is sufficiently strong (i.e. intuitively understood), that he will change his mind about the target. However, although Tom made correct correspondences between objects and relations in the base and target and realized the implication of this mapping (equal forces), he appeared quite unwilling to accept the conclusion of this analogical inference. It is worth mentioning that in an earlier study, on a similar problem (a bowling ball striking a bowling pin), only 5% of the students answered correctly that the bowling ball and pin would exert equal forces on each other during the collision (Brown and Clement, 1987a). This question was administered after a full year of traditional high school physics instruction. Thus the billiard balls problem may have been drawing out a particularly deep-seated misconception, that is, force as a property of objects (vs. forces arising as a result of interactions between objects) with some objects being more "force-full" than others.

In this light, it is perhaps not surprising that Tom made such little progress. However, this case is anomalous in that Tom apparently had everything necessary for transfer of understanding from the base to the target. He had a strong intuition about the base, he correctly mapped the base onto the target, and he could not escape an internal sense that the analogy was apt. However, there was no successful development of a new understanding. This anomalous case study leads to the hypothesis that when students have a deep-seated misconception, they may require an analogy which is not only intelligible (i.e. one for which they can make correct corresponsences), but which also helps provide a plausible explanation for the analogous phenomena in the target. In the following section we discuss the potential of "explanatory models" to provide this plausibility.

General discussion

In this paper we have examined case studies illustrating the use of analogies in teaching to overcome misconceptions. We contrast the use of analogies here to more typical situations in which analogies are used to help students gain a grasp of situations for which they initially have little or no knowledge. In the approach employed here, analogies are used to help students change their existing, and often deeply rooted, preconceptions of target situations. In what follows we attempt to identify those factors which are important to producing conceptual change.

Case studies 1 and 2 provide examples of successful interventions in which there was some evidence for conceptual change. Case studies 3 and 4, however, provide examples of instructional interventions which failed to produce any observable conceptual change. In case study 3 it seems clear why the bridging approach failed – the student never came to view the anchor and the target as analogous. Further, it would have perhaps been impossible to bring her to such a realization through bridging if the symmetric anchoring conception used was brittle, that is, unable to tolerate small changes in attempts to bridge to the target.

However, in the fourth case study it is more difficult to articulate why the intervention failed, since the elements necessary for analogical transfer appeared to be present. In order to articulate the reason for the failure in the fourth case study, it is necessary to take a closer look at the successful interventions. For the sliding puck and book on the table problems, it appears that both Mark and Tom were given more than simply a demonstration of analogical relatedness, they were helped to construct a new "explanatory model" of the target.

Explanatory models

Hesse (1967) and Harre (1972) identify two types of scientific analogue models:

1) A model which shares only its abstract form with the target (Hesse cites hydraulic models of economic systems as one example). Such an analogue may happen to behave like the target case and therefore provide a way of predicting what the target will do. Here we call this an *expedient analogy.*
2) A model that has become in Harre's terms a "candidate for reality," in which a set of material features, instead of only the abstract form, is also hypothesized to be the same in the model and the target situation (these features are often unobservable in the target at the time). As an example, consider the elastic particle model for gasses, in which a gas is hypothesized not only to *behave like* billiard balls bouncing around, but to actually *be* tiny particles bouncing around.

We refer to the latter type of model as an *explanatory model.* Thus an explanatory model is a predictive analogy in which elements of the model are seen as being in or operating in the target. Although we discuss the distinction between expedient analogies and explanatory models as a dichotomy, this distinction is more likely a continuum, with some analogues having characteristics of both. See Clement (1989) for further discussion of these issues.

Given that the analogy relation is accepted, what determines whether an analogy, such as the Mr. T example, will lead to an explanatory model for the student? We hypothesize that in the successful cases, the anchoring example is used as a basis for developing an image of a structure or mechanism operating in the target. At least two factors may make this difficult for a student: difficulty with the necessary spatial image manipulation skills (as in explaining the phases of the moon); or competition with a prior conception (e.g. seeing tables as rigid barriers rather than elastic sources of force). For the book on the table, the explanatory model is the image of the of the deformation of a springy substance causing a reaction force. This is fairly easy to see and feel in the case of the spring, but in the case of the table, we hypothesize that this imageable mechanism must be projected by the student into the image of the table where the deformation is ordinarily unobservable. For the sliding puck problem, the explanatory model of the puck and floor as bumpy provides the imageable mechanism of microscopic bumps in the floor deforming and providing a reaction force against bumps in the bottom of the puck. Again, we hypothesize that this mechanism must be projected by the student into the image of the puck on the floor, since it is not observed.

Such explanatory models might seem more plausible or compelling to the student than an expedient analogy, since key elements of the model are seen as actually operating in the target. Thus the model involves concrete as well as abstract similarity in that the model provides a structure or mechanism that could plausibly be imaged in the target. Such plausibility to the student may be crucial in effecting conceptual change (Posner, Strike, Hewson and Gertzog, 1982). In contrast to when he was dealing with friction, Tom was apparently unable to construct a new explanatory model of the billiard balls situation (compare Figures 3 and 5). Although he sensed the aptness of the analogy to Mr. T and the railroad cars, this did not provide him with a new way to think about the billiard balls situation, it simply implied that his view of unequal forces was incorrect. Thus, he was simply left with a paradox: "Why do I think equal force in this situation, but not in this situation, when I cannot see how they are different?" During the interview he found no way of resolving the conflict and ended the session confused. Recently we have used a different approach in classroom lessons to help students construct an explanatory model of situations like the billiard balls. Using a bridging strategy we attempt to help students view the surfaces of the billiard balls as compressible (Camp, Clement, Schultz and Brown, 1988). It is our experience that the idea of equal compression of the billiard balls on impact can help the students make sense of the equal forces.

Abstract transfer versus explanatory model construction

These results may indicate a need for a more comprehensive theory of analogical learning than has been provided to date. A widely accepted view considers that an analogy is beneficial because it helps the student view the target in a more *abstract* way. By helping the student focus on the shared relational structure between the base and the target and downplaying the significance of the actual objects and object attributes, the analogy can help lend relational structure to the previously poorly structured target situation (Gentner, 1983, 1989; Gick and Holyoak, 1980, 1983; Holland, Holyoak, Nisbett and Thagard, 1986; Holyoak and Thagard, 1989). The learner is left with a mental representation of the target in which objects and object attributes are less salient, and abstract relational structure is more salient.

By contrast, in the successful interventions here, the analogies appeared to help *enrich* the students' conceptions of the target situations rather than (or at least in addition to) helping them view the situations more abstractly. We hypothesize that this enrichment of the target with new objects, object attributes and causal relations (e.g microscopic bumps, flexibility and bending causing forces) may be necessary for conceptual *re*-structuring. When such enrichment of the target was not present, Tom was unable to change his conception of the billiard balls situation, even though he was able to make correct correspondences to a better understood base.

This contrast between abstraction and enrichment in analogical learning is further developed in Table 1 and in Figures 6 and 7. Figure 6 illustrates abstract transfer of relational structure. In (a), the dotted circle indicates that the student has little prior understanding of the target (T). In (b), the analogous, better understood base situation (B) is introduced. This leads to mapping and the transfer of abstract relational structure to the target in (c). Finally, in some cases (d) an abstract schema (S) is induced which consists of the common relational structure. Figure 7 illustrates target enrichment and explanatory model construction.

Table 1. Comparison of two approaches to using analogies in instruction: abstract transfer and explanatory model construction

Abstract transfer	Explanatory model construction
Goal – conceptual growth	Goal – conceptual change
Student has little or no understanding of the target situation	Student understands the target situation, but understanding is non-normative
Student understands the base situation	Base situation (called an anchor) draws out a valid physical intuition
Student accepts that the analogy relation is sound (often simply accepting the authority of the teacher or text)	Student initially has difficulty accepting that the analogy relation is sound
Analogy helps provide abstract structure to the target situation by relating it to an already understood situation	Target already structured in student's mind, but this structure needs to be changed. Analogy helps student restructure by helping student construct a new explanatory model which enriches the target situation.
Analogy is presented (e.g. in text or lecture)	Student is engaged in a process of analogical reasoning (e.g. tutoring or class discussion) to evaluate (and occasionally generate) the analogies

For purposes of clarity, this diagram clearly oversimplifies what in fact can be a complex design process of generation, criticism, and modification (cf. Clement, 1989). In Figure 7 (a), the solid square indicates prior understanding of the target situation (T), although this understanding is non-normative (e.g. that no force is acting in a direction opposite to the motion of a sliding puck, only a directionless resistance). In (b), the analogy relation between the anchor (A) and the target is initially rejected, or at least questioned (e.g. the relation between brushes and a puck sliding on the floor). In (c), the target is enriched with new objects, object attributes, and/or causal relations (M') (e.g. the floor and puck being microscopically "hilly and rough," giving rise to a directional force as the bumps in the floor bend and push back). The circle around (T) indicates that the student's conception of the target has been changed. In some cases (d), a generally applicable explanatory model (M) arises from this enrichment of the target (e.g. all objects are microscopically bumpy, giving rise to directional friction forces for any two surfaces in contact). Such a model, although generally applicable, differs from the

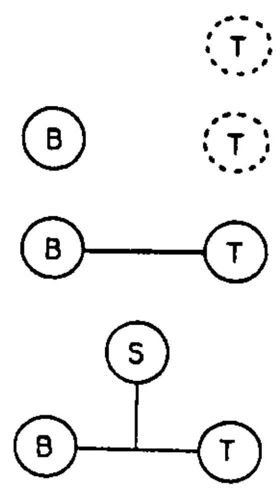

Figure 6. Abstract Transfer of Relational Structure: a) Dotted circle indicates target situation (T) is poorly understood. b) Analogous base situation (B) introduced. c) Mapping and transfer of abstract relational structure to target. d) Abstract schema (S) induced which consists of the common relational structure.

abstract schema in Figure 6 in that it shares more than its abstract form with situations to which it is applied.

Enrichment and explanatory model construction is not offered as an alternative to abstract transfer of relational structure, but rather as an indication that a comprehensive theory of analogy must account for both abstraction and enrichment. Many questions remain which must be addressed, such as:

1) Are target enrichment and explanatory model construction necessary for conceptual change via analogical reasoning?
2) It appears that the use of bridging analogies can help promote explanatory model construction. Exactly how is model construction facilitated by bridging?
3) What might be some other strategies for helping students construct explanatory models, keeping in mind the need to coordinate students'

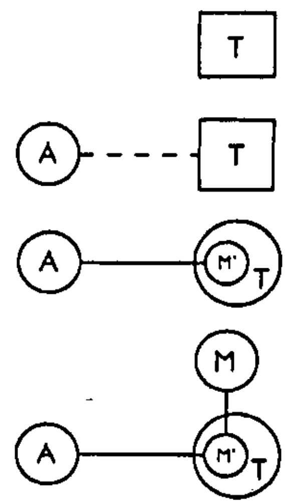

Figure 7. Target Enrichment and Explanatory Model Construction: a) Solid square indicates non-normative understanding of the target situation (T). b) Analogy relation between anchor (A) and target initially rejected. c) Target enriched (M') and conception of target changed. d) Generally applicable model (M) arises from enrichment of target.

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