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Mapping a Student's Causal Conceptions From a Problem-Solving Protocol

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INTRODUCTION

The problem of how to describe the structure of a student's current conceptions in a given area is a fundamental one for researchers who seek to develop a theoretical foundation for cognitively oriented instruction. Recent developments in the physics teaching community, for example, have emphasized cognitively oriented approaches to teaching and the need for understanding the cognitive processes that underlie one's ability to "do" physics. Ideally, we would like to have a picture of the kinds of knowledge structures and reasoning processes that are present in beginning students and that are present in experts. Detailed descriptions of experts' knowledge structures, including those tacit knowledge structures not represented explicitly in the curriculum, would presumably help to define more clearly what is to be learned by the student. Detailed descriptions of beginning students' preconceptions and misconceptions would have value not only as a sophisticated evaluation tool, but would also make it more possible to take common preconceptions and misconceptions into account during instruction.

This paper attempts to show that it is possible to study systematically certain types of beginning students' conceptions in physics; specifically, causal conceptions in mechanics. The paper examines the conceptions a freshman student uses to understand a simple physical system involving the horizontal motion of a cart launched across a table. The task given to the student does not ask him to find a long series of actions which will solve a problem. Rather he is asked for a prediction and explanation of the effects on the system resulting from a single action. Protocols of such explanations are particularly interesting because they tend not to be limited to formal, deductive arguments, but to include informal arguments that reflect the structuring of the subject's physical intuitions.

The methodology used in this study involves two phases: obtaining problem-solving protocols via taped interviews, and analyzing these protocols to produce a model of the conceptions that underlie the student's responses in the interview. Several considerations are important to the success of this technique. An important consideration during the interview process is the attempt to encourage the student to express himself verbally as he thinks through a problem. The interviewer must also search for questions which match the level of the student's conceptions. An important consideration during the analysis phase is the attempt to model the student's conceptions at a level that is neither simpler nor more complex than the level reflected in the student's comments. In addition, the analyst must be ready to encounter conceptions that are qualitatively different from the standard conceptions used by physicists. Even when the student uses a standard term like "friction," only repeated probes by the interviewer can indicate whether the student's meaning for the term is equivalent to the physicist's.

For a discussion of the methodology of protocol analysis, see Witz and Easley (to appear), Easley (this volume), and Newell and Simon (1972).

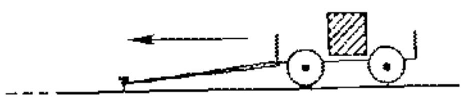

Figure 1. Launching a Cart

TRANSCRIPT ANALYSIS

The example discussed in this paper concerns a first-semester freshman engineering student named Mark who has had a course in high school physics but who has not yet had a course in college physics. The verbatim transcript sections shown below are from a videotape of Mark working on the following problem: he launches the cart from an elastic band attached to the table as shown in Figure 1 and watches it roll to a stop. When asked, he says that the cart won't go as far if the band isn't stretched as far, and that the car attains its maximum speed near the point where the band goes slack. Both of these predictions are in agreement with physical theory. The interviewer then asks Mark to predict the effect on the motion of putting a metal weight in the cart. (Adding the weight to the cart will in fact reduce the distance traveled; this can be shown theoretically by energy considerations.)

TRANSCRIPT[1]

I = Interviewer (Clement) S = Student

Section 1

(S rolls cart back and forth several inches with right band)

I: "What would happen if we put the weight in, (puts 500 g weight in cart) do you think—and used the same stretch for the rubber band? Do you think it would affect the maximum speed?" 1

S: (12 seconds pause) "Um, yes I do (lifts cart up with weight in it)—'Cause it seems like an awful, like a pretty heavy weight." (Begins to set up cart for another launch.) 2

I: "How would it affect it, before you try it out? . . ." 3

S: "It would affect it, it would slow it down, I would think." 4

1. Dashes (--) indicate pauses.

I: "But why, why would that happen?" 5

S: "Well, you got a large, a larger mass that you have to pull.— (Rolls cart back and forth several inches with band stretched). It's just not gonna have as much zing to it, you know, that, you don't get—the strength of the elastic is gonna not really be strong enough to pull it as fast as it did before." 6

We can represent the major conception behind Mark's statements here using the diagram shown in Figure 2. This conception could be expressed verbally in the statement: "If one increases the mass of the cart, one expects the maximum speed of the cart to decrease." (We assume that the same conception embodies the expectation that decreasing the mass would mean an increase in speed.) Thus the subject's conception is thought of as an expectation of the results of a contemplated action. The numbers on the arrow in the diagram indicate specific lines in the transcript from which the presence of the conception is inferred. We call this a semi-quantitative conception because it anticipates the *direction of change* in a dependent variable (cart speed) that will be caused by a change in an independent variable (mass of the cart).

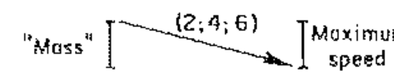

Figure 2. Map of Conceptions for Section 1 of the Protocol

This type of conception is more elaborate than the strictly qualitative conception that the weight will affect the speed in some unspecified way, but it does not go so far as to provide a quantitative mapping from particular values of the independent variable to the dependent variable. Thus the diagram is an attempt to represent the conception as it exists in Mark at this time—without making it more simple or more complex than it really is. The system of notation is adapted from a notation used by Driver (1971). She found that the eighth graders interviewed in her study used semiquantitative conceptions spontaneously to explain various physical phenomena. This type of conception is also related to the "qualitative operations" discussed by Inhelder and Piaget (1958) that precede the use of proportional laws by children as a means of understanding simple physical systems. We have found that engineering students enter college with many physical conceptions at this same semiquantitative level.

Next, the interviewer asks whether putting the weight in the cart will also affect the total distance traveled by the cart.

Section 2

I: "OK. Before you try it out, how do you think it would affect the, uh, distance that it goes?" 7

S: (Lets go of cart so that band pulls it forward but stops it with left hand after it travels only eight cm.) "It wouldn't go as far, I don't think." 8

I: "Why would you predict that—" 9

S: "(a) Wait a minute, wait a minute. (17 seconds pause) (b) Hm—It'd probably go almost as far. (c) (Rolls cart back and forth, letting it coast a little in each direction) Just the weight bearing down on the surface [of the table] is probably why I think it wouldn't go as far. (d) But it, it'd probably make it almost quite as far, I would think." 10

I: "OK. What are the factors that make it go farther, or—as far with the weight in it?" 11

S: "(a) One is you have the added, the added mass, (moves cart back and forth, letting it coast) so it's more weight on the table. (b) But then again you have the added mass—um, that's already moving. Once you started moving it, it's gonna help it move it, even, (holds hands 10" apart and moves them simultaneously several inches back and forth above the cart) it's gonna help it keep going a little bit (moves cart back and forth slightly)." 12

I: "With more mass?" 13

S: "(a) Yeah. But I don't think that'll overcome all the friction (brings side of right hand down on back edge of cart wheels several times until it moves) that it'll give it. (Starts cart rolling with hand, moving other hand slightly ahead of cart until it stops rolling on its own) (b) See, once it starts rolling, it rolls pretty good." 14

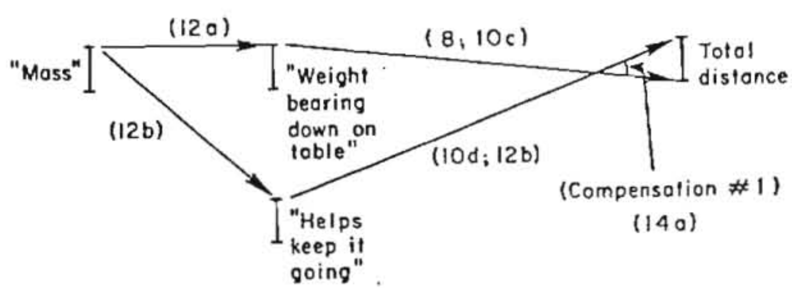

Figure 3. Map of Conceptions for Section 2 of the Protocol

The diagram in Figure 3 gives a model of the conceptions that are active in Mark as he generates his comments in lines 7-14. Basically, his conceptions take the form of a *network of causal expectations*. The diagram indicates that Mark considers two competing factors that will affect the distance traveled by the cart. First, the increased mass will increase the "weight bearing down on the surface [of the table]." This will in turn decrease the total distance traveled. This type of relationship is indicated in the diagram by the notation

A|↗|B|↘|C, translated: "Increasing A causes an increase in B," and "Increasing B causes a decrease in C." Secondly, however, increasing the mass in the cart according to Mark also "helps it keep going more," which has an opposite effect and causes an *increase* in the total distance. Thus Mark expresses his understanding of a relationship of *compensation* between two competing intermediate variables affecting the total distance in opposite ways. These conceptual structures appear to be intuitive in the sense of not being based simply on verbal facts learned in school. Since both of these variables are increased in the experiment, Mark has some difficulty in predicting the result, as evidenced by the way he changes his answer in line 10.

At this point Mark diverts his attention momentarily to observe that the cart seems to roll somewhat more easily when he pushes it to the right than when he pushes it to the left, and he conjectures that the table may not be perfectly level. He then returns to the problem at hand, and in response to a question from the interviewer integrates his conceptions from the first and second sections to produce another compensation relation.

Section 3

S: "(a) Um, I would say the added, the added weight probably doesn't do all that much except to give it a little, not—you know, a little bit of added friction, (b) and I'm sure it won't go as fast off the start, just 'cause the strength of the elastic band isn't—(stretches band between fingers)" 15

I: "Would that affect it?" 16

S: "What?" 17

I: "How far it goes?" 18

S: "The strength of the band?" 19

I: "No, it won't go as fast at the start, you said." 20

S: "(a) Yeah. Uh, oh—(scratches head) How far it goes?—Yeah, it'll affect how far it goes, (b) but this added mass is gonna tend to, (rolls cart back and forth several inches) I think, keep it rolling maybe a little better even if it doesn't have that maximum speed." 21

I: "Uh huh.—Why does it keep it rolling, just to have more mass? Does that just seem that way, or is it like—?" 22

S: (Continues rolling cart back and forth, letting it coast.) "I don't know, you know, like, when a car goes down a hill?" 23

I: "Yeah." 24

S: "Or when you go down sledding? if you have two people on a sled, it goes better than if you have one person?" 25

I: "Hm." 26

S: "Just, uh—(moves cart back and forth) it seems the added mass would just give it more of a, (moves left hand with back of hand leading in quick motion over the cart's original path) more momentum maybe, once it gets started." 27

Figure 4 shows how the two preceding diagrams can be combined to account for many of Mark's comments in this section. He expresses a second relationship of compensation in line 21 between increased "momentum" and decreased maximum speed. These two factors have opposite effects on the total distance traveled. Thus he is able to *coordinate* his conception involving maximum speed from the first section with the conceptions he expresses in the second section.

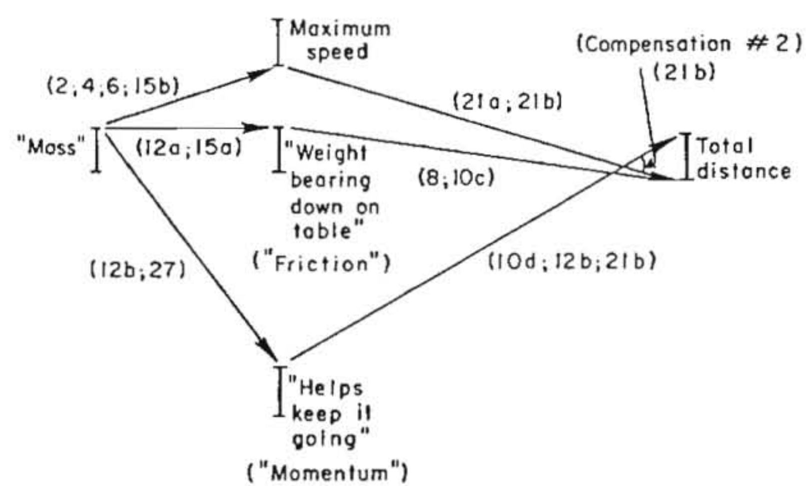

Figure 4. Map of Conceptions for Complete Protocol

This coordination, however, appears to be at least partially provoked by the interviewer when he asks Mark specifically about whether maximum speed will affect total distance. Had Mark made this connection in a spontaneous manner, he would have been linking two separate conceptual structures spontaneously via a variable common to both structures. We suspect that this kind of coordination process is an important one and we are attempting to study it in other protocols. The process may underlie the ability to plan the linkages between theory domains that are necessary in solving multi-step problems in mechanics. In the previous section (lines 10-12) where Mark suddenly recognizes the first compensation relationship, he indicates that he can make such coordinations spontaneously under certain circumstances.

Mark was one of a group of 15 freshmen who were given the cart problem, but only his protocol will be discussed here. All of these students were able to give semiquantative predictions and Mark's response was fairly typical although the

number of variables he relates semiquantitatively (five) is somewhat above the average for the group. Many, but not all, of the other students detected compensation relationships and generated analogous cases in a similar way.

It is difficult to score Mark's performance on the question as correct or incorrect, because he never does make a strong prediction about the effect added mass will have on the distance the cart travels. For the purpose of studying his conceptions, however, labeling his answer as "correct" or "incorrect" is actually an irrelevant concern. Indeed, the interesting part of his response is not whether it is correct, but the picture his *explanations* give us of his highly structured conceptual model of the situation.

However, some issues cannot be resolved on the basis of this short interview. First, one can ask: "Are Mark's conceptions a result of his high school physics training, or are they primarily self-constructed?" We suspect that the answer here is, "primarily self-constructed," but we really cannot be sure of this on the basis of the written transcript. A second question is: "Since Mark physically manipulates the cart to some extent, are some of his conceptions actually constructed by him on an empirical basis during the interview, rather than being preconceptions?" It seems unlikely that Mark's conceptions are constructed "from scratch" during the interview, but we cannot be certain about this issue either, on the basis of the transcript. Given that we cannot firmly resolve these issues concerning the origins of Mark's conceptions, the transcript is nevertheless a rich source of information concerning the nature of his current conceptions.

A primary source of confidence in our model of Mark's conceptions (as represented in Figure 4) are the multiple entries of transcript line numbers attached to each semiquantitative relationship. There are at least two points in the transcript supporting each relationship shown in the diagram. This means that the diagram is based on repeated *patterns* in the content of Mark's comments. This gives us a measure of confidence in the validity of our micro-theory of what his conceptual structures are like, because we have exhibited a network of ties between specific aspects of the theory and specific observations from transcript data.

STRENGTHS AND LIMITATIONS OF MARK'S CONCEPTIONS

It is instructive to consider some of the strengths and limitations of Mark's conceptions. He seems to shift back and forth on the question of the effect of adding mass, first leaning toward predicting a decrease in the total distance traveled and then toward an increase. This is understandable, since a conceptual system at the semiquantitative level is powerful enough to *1.* model several of the causal relationships that are operating in the experiment, and 2. predict the effect of a change in either maximum speed or friction on distance traveled; but his conceptual system is not quite powerful enough in this case to predict a definite answer for the question of how adding mass will affect the distance traveled. Thus his uncertainty in this case is an effect produced by the limitations of the knowledge structures available to him, not an effect produced by careless reasoning.

Several other limitations of Mark's conceptions can be noted. He uses the terms *friction, mass,* and *momentum,* but it is not at all safe to assume that these terms carry the same precise meaning for him that they do for the physicist. Thus, we must not make the mistake of assuming a one-to-one correspondence between the external use of a standard term and the internal use of a standard concept. For example, he uses the word 'friction' in lines 14a and 15a. The physicist here would use this term to refer to a force pushing back on the car. Mark, however, does not give evidence of having this concept. Instead, he says in line 10c: "Just the weight bearing down on the surface is probably why I think it wouldn't go as far." This comment is similar to those of several other freshmen we have interviewed who appear to conceive of friction as purely a downward force which is seen to retard motion solely by reason of being in a different direction from the motion. So one should give Mark credit for recognizing that increasing the mass will cause more of a retarding influence, but one cannot assume that his conception of friction is identical to the physicist's conception, even though Mark uses the same term that the physicist uses.

Similarly, it is not clear that Mark differentiates between the meanings of his terms *weight* and *mass*. This limitation becomes clearer later on when he is asked to predict what would happen if the same experiment were tried in outer space. He predicts that adding mass will have no effect on the maximum speed, contrary to the physicist's point of view. Also he uses the term *momentum* at the end of the protocol, but it is interesting to examine the way in which he separates his comment that the added mass will reduce the maximum speed attained during the first part of the motion from his comment that the added mass "helps it keep going" in the latter part of the motion. The physicist conceives of the inertia of a quantity of mass as the resistance of that mass to any change in velocity, whether it be acceleration from rest or deceleration from a state of motion. However, the protocol does not indicate that Mark has an integrated conception which assimilates these two situations. Rather, it indicates that he has separate conceptions for thinking about each of them.

Finally, Mark generates two analogous situations to explain the way in which added mass "helps it keep going." He refers to the way "a car goes down a hill" and to the way a sled "goes better" with two people rather than one. This type of spontaneous analogy construction on the part of the student in order to make sense of relationships between more abstract concepts like momentum and force is certainly to be encouraged. But it is clear from the transcript that the analogies are not evaluated with the level of precision required in physics, and this is an ability that Mark needs to develop further. See Clement (1977b, 1978) for further discussion of spontaneous analogies.

Given these limitations in Mark's performance, we were still impressed with the complexity of his knowledge structures in this area and with the potential power of his semiquantitative reasoning processes. First, he does not simply make a prediction from his global impression of the cart's behavior. He engages in an *analysis* of the situation by successfully isolating several variables that will affect the cart's motion and by considering compensation relationships between these variables.

Second, we can contrast Mark's analysis of independent factors affecting the cart with the type of symbol manipulation response we would expect from other students who have had a course in mechanics but who have "gotten through" largely by memorizing formulas. Typically, these students have not developed causal conceptions at a deeper level of understanding that provide a foundation for understanding the quantitative relationships in the formulas. Such students have difficulty answering a question about a formula that goes deeper than the superficial level, such as: "Can you give an intuitive justification for the formula, F = ma ?" An example of an answer that would indicate some intuitive understanding of the principle is the following: "I can think of pushing a certain mass to accelerate it. If I want a larger acceleration I'll need a larger push. If I want the same acceleration with a larger mass, I'll also need a larger push. Therefore the formula makes sense." Or consider the following excerpts from a response given by Ron, a more advanced physics student:

I: "I'm wondering if you can explain a rationale for the formula F = ma, that makes sense to you . . ." 1

S: "Alright . . . let's choose two objects. If we exert the same force to both these objects, which differ in mass, the result is gonna be the lighter object will be displaced at a greater rate . . ." 2

S: "And by increasing 'm,' 'a' will have to decrease. 3

These are semiquantitative arguments that indicate that the formula is grounded intuitively at this level for the student and is a principle that he believes in with some conviction. Mark's arguments are of this same form. He is engaging the problem at a deeper conceptual level than a student who can merely juggle formulas algebraically.

Third, Mark's conceptual system is very different from a memorized set of isolated facts. We can describe this system, represented in Figure 4, as a network of causal expectations. Each A↕ → ↕B relation in this network represents a dynamic, action→result expectation. These form an interconnected network of action-oriented conceptions rather than a collection of isolated facts.

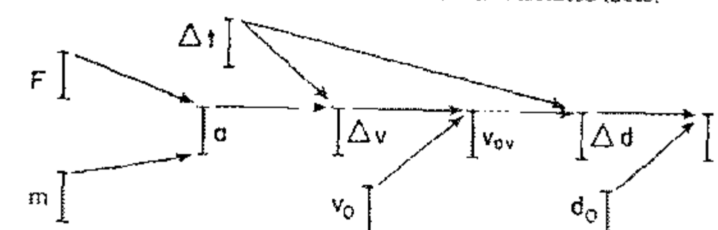

Figure 5. System of Conceptions for Understanding the Movement of a Particle Under a Constant Force

Fourth, although semiquantitative knowledge structures lead to predictions that are less precise than those from structures involving quantitative functions, they can still allow for a significant degree of predictive power. For example, the diagram in Figure 5 models a system of semiquantitative conceptions that can underlie a physicist's understanding of the movement of a particle under a constant force. Such a conceptual system can provide a *causal understanding* of this type of motion in terms of finite intervals at a pre-calculus level. As such, it can underlie and support the more refined relationships represented in the formula:

$$\frac{F}{m}\,\frac{\Delta t^2}{2} + v_0\Delta t + d_0 = d$$

It is intriguing to note that such a conceptual system seems well-adapted for the task of selectively assimilating those problem situations where the use of the associated formula is appropriate and thus providing the subject with a semantic basis for deciding *when to use* the formula. Simply memorizing the formula provides no such knowledge.

We can list some characteristics of the inferences that appear to be possible using semiquantitative structures:

1. the predictions made are transformational rather than static in the sense that one predicts that a *change* in A will produce a *change* in B;
2. such $A \rightarrow B$ anticipations can be linked to inference chains of potentially unlimited length;
3. such $A \rightarrow B$ anticipations can reflect empirically observed relationships as well as causal theories (these two kinds of relationships may require different cognitive explanations at a deeper level);
4. there is an implicit logic for how such anticipations can be combined; for example $A\uparrow \rightarrow \uparrow B$ implies $A\downarrow \rightarrow \downarrow B$ and $(A\uparrow \rightarrow \uparrow B,\ B\uparrow \rightarrow \uparrow C)$ implies $A\uparrow \rightarrow \uparrow C$. Significantly, the students we have interviewed all seem to be at home with these implications—these appear to be *natural inference patterns* that make sense to them intuitively;
5. several independent variables can be linked to a single dependent variable, and this can be represented by tree-like structures such as $\begin{array}{l} A\uparrow \searrow \\ \quad\quad\ \uparrow C \\ B\uparrow \nearrow \end{array}$;
6. these tree-like structures can provide a basis for representing the control of variables in an experiment and for compensation relationships between independent variables;
7. more complex causal conceptions can be represented by the analyst as lattices or feedback networks using the same elements. Thus the potential power of causal networks of this type appears to be far from trivial.

We can now summarize our discussion of the several weaknesses and strengths in Mark's conceptions concerning the cart experiment. His concepts of mass, friction, and momentum do not seem to be as refined as those of the physicist. His use of analogies is not as precise. He almost never refers to quantitative functions. On the other hand, he is able to isolate several of the most important relevant variables, including the effect of increasing weight on the momentum of the cart. He also identifies compensating variables. His conceptions appear to form a network of causal chains which give him a first-order understanding of the system, and this integrated conceptual structure is quite different from a set of memorized formulas. Finally, certain types of natural and potentially powerful reasoning processes seem to be associated with knowledge structures of this type.

IMPLICATIONS FOR INSTRUCTION

Mark's conceptions are *not* equivalent to those that a physicist would use, but our analysis has shown that he is definitely not a "blank slate." This raises the possibility that certain of Mark's conceptions can serve as starting points for learning—that Mark can build on what he already knows by modifying his existing knowledge structures rather than starting from scratch. The way in which students' preconceptions are taken into account in a particular course

will depend on the educational goals of the course. In the case of courses where the student's primary goal is to gain an understanding of Newtonian physics, the student needs to become aware of the similarities and differences between his intuitive preconceptions and the Newtonian point of view. By analyzing Mark's conceptions we have already identified three specific points where he should be able to build on his current ideas: discriminating between mass and weight; elaborating his concept of surface friction by establishing a causal relationship between normal forces and retarding forces; and integrating two concepts of inertia as resistance to acceleration and deceleration. It is unlikely that these changes in his beliefs at a causal level will happen automatically simply as a result of memorizing formulas. It is clear that he will need to construct new conceptions at a semiquantitative level in addition to learning new quantitative relationships. These are the conceptions that will provide a semantic underpinning for the equations he learns. Building on his existing conceptions as outlined above would appear to be a more fruitful approach to this task than attempting to build a new conceptual system from the ground up. Thus, we suspect that networks of semiquantitative conceptions of this type represent an important level of knowledge in students that must be taken into account in standard physics courses if superficial formula memorization approaches are to be avoided.

However, the ability to identify students' conceptions should also have particular value in courses which take the development of methods of scientific inquiry as their primary goal. Such courses may encourage students to: *1.* articulate their preconceptions as hypotheses; *2.* design experiments (or thought experiments) to test them; *3.* modify and refine their conceptions; and *4.* select the most successful theories from those shared in class discussions. Students who are successful in completing such cycles go through an important learning experience regardless of whether their working hypotheses are correct from the physicist's point of view. Conceptual mapping techniques should make it possible to *1.* identify appropriate topics for such courses which tap rich sets of preconceptions in students and *2.* document changes in students' knowledge structures in such courses.

Clearly it is not possible for an instructor to analyze each student's preconceptions at this level of detail and respond accordingly to each student individually. But while it would be hard to find another student whose conceptual system matches Mark's exactly, individual elements of his system do appear to be identical to the conceptions of many of the 15 other freshman students we have studied using the cart problem. Thus there appears to be a small set of common preconceptions concerning momentum, friction, force, velocity, etc., and there is a need to compile a catalogue of these common preconceptions as an aid to teachers.

The fact that Mark does not give a decisive and correct answer to the question posed about whether the cart will travel further means that his *performance* on this question would traditionally be interpreted as poor. Yet, as we have seen, Mark does some impressive thinking about the problem in terms of his own conceptions. A wrong answer in this case does not imply that no useful thinking has taken place. This indicates that a special kind of patience and sensitivity is going to be required from teachers who wish to help students develop principles that are anchored in physical intuition.

DIRECTIONS FOR FUTURE RESEARCH

Models of student knowledge in the form of semiquantitative structures like those discussed here capture important aspects of intuitive conceptions of force and motion. As with all models, however, we can hope to eventually expand and refine them as we become more sensitive to the fine structure of the phenomena being observed. I will comment on several limitations of the analysis given here as an indication of directions for future research: first, the question of how the conceptions are accessed or activated; second, the need to give a more detailed description of what the "units of representation" or "units of meaning" are in Mark's knowledge structures; and third, the need to somehow account for Mark's hand movements which seem to parallel his explanations in such an important way.

The question of how Mark activates or accesses his conceptions is a difficult one to answer on the basis of the short transcript analyzed here. Since it seems that subjects are often not conscious of the access process, we will need case studies involving the same subject working on several related problems to make inferences about which aspects of a situation are involved in triggering a particular conception.

With regard to the second question, the static collections of symbols used in these diagrammed cognitive models are necessary for purposes of notation, but, like equations in physics, they can be used to represent elements that are either static or dynamic. Although the semiquantitative diagrams that we have used as a first-order model of the student's conceptions are discrete relational structures, this does not commit us to a position on the issue of whether the internal cognitive structures they represent are best thought of as static symbols in the form of propositions or dynamic (time-varying) patterns of functioning in the form of action-oriented schemes. Cognitive models involving continuous, dynamic structures have been proposed recently by Witz and Easley (1971, and forthcoming), and Shepard (1978).

Consider the case where Mark says:

12(b) "But then again you have the added mass—um, that's already moving. Once you started moving it, it's gonna help it move it, even (holds hands 10" apart and moves them simultaneously several inches back and forth above the cart) it's gonna help it keep going a little bit (moves cart back and forth slightly)."

In the first order theory of Mark's knowledge structure already given, we represented the conception behind this statement with a structure in the form $A|\rightarrow|B$ where A is a conception of "mass" and B is a conception of "tendency to keep going." However, when conceptions like these are eventually modeled at a deeper and more detailed level, it may be in terms of either dynamic action schemes and kinesthetic imagery with characteristic time constants governing their coordination, or it may be in terms of static relational structures with "slots" to be instantiated and inference rules for replacing one symbol with another.

These choices reflect a current area of controversy over the nature of internal representation and the nature of the units of meaning in cognitive psychology. The resolution of this issue will come only after much more empirical and theoretical work has been done, but the transcript analyzed here does suggest

that while nondynamic models may account for some features of the behavior, dynamic, action scheme models will be needed to account for other features. That is, we must consider the possibility that going through an action vicariously over a period of time and vicariously experiencing its effect, are activities intrinsic to this kind of causal knowledge.

Several factors lead us to consider this possibility. The semiquantitative relations used to model Mark's conceptions are of the form $A|\rightarrow|B$, where this means that a *change* in A leads to a *change* in B. It is very natural to propose that this $A|\rightarrow|B$ notation represents an action-based scheme for doing action A and anticipating the direction of change in B. The vicarious operation of such a scheme without external actions could involve internalized actions and kinesthetic and visual imagery. The fact that Mark's statements are accompanied by hand motions and hefting-like manipulations of the equipment also suggests that action-based structures involving kinesthetic feedback are central to Mark's thinking in this interview. This is especially true whenever he talks about the way the added weight will affect the cart's motion by being "a large mass that you have to pull" at the start, and by "helping it keep going" once it gets started. During almost all of the time he gives his explanations he is looking directly at the cart. The hand movements take place over periods of seconds and are often repeated several times. He also tends to redescribe and rephrase several of his explanations as he stares at the cart.

All of these observations suggest the presence of intuitive nonverbal conceptions which become active in Mark over periods of two to 10 seconds and which are responsible for his awareness over these time periods of the visual and kinesthetic effects of some imagined action involving the cart. This suggests that the knowledge structures responsible for Mark's physical intuitions, like overt actions, must *function continuously over a period of time* and *involve the motor-kinesthetic and visual systems at some level* in order to be meaningful. If these preliminary indications are confirmed, it will be necessary for theorists to be as creative and open-minded as possible in order to develop more detailed models of physical intuition that account for these aspects of the behavior.

SUMMARY

We have tried to show that it is possible to study systematically students' conceptions in physics, specifically in the area of mechanics, by using protocol analysis techniques. This can be done even when the basic concepts that the student uses are physical intuitions that are not equivalent to standard concepts used by the physicist. Such an analysis provides a much richer source of information about students' knowledge structures than do written tests.

With regard to methodology I believe that we are at a stage in the science of studying complex cognitive processes where the primary need is to develop viable qualitative models of cognitive structures. The analysis of many more protocols at various levels of detail should provide a needed background of rich phenomena as a fertile ground for the development of such models. The inclusion of verbatim sections of transcript in such studies provides an important constraint on the model construction process, since the requirement that a proposed model be consistent with as many aspects of the transcript as possible is a demanding one in the case of extended protocols.

In the analysis given here, the student's conceptions were modeled as a network of causal expectations. It was suggested that causal conceptions of this type represent an important level of knowledge in students that can provide an intuitive foundation for understanding many quantitative laws and that students' preconceptions are natural starting points for building such a foundation.

The fact that this type of conceptual mapping is possible opens up the potential for describing differences in the knowledge structures of an individual at two different points in time. This in turn holds potential for the development of more sophisticated evaluation tools; and the development of new instructional strategies which take typical preconceptions into account and which foster a deeper level of understanding in students.

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