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ABSTRACT

By studying many observations from recent research dealing with beginning physics students' conceptions about forces and motion, this investigation produced a framework within which this research can be organized. The framework summarizes the mechanisms of force invoked by students in particular situations, and it describes the features of physical situations that students believe will modify the relative sizes and forces. Finally, the framework suggests some of the ways students mediate between various forces when predicting or explaining what will happen in a given situation. Using the framework of students' ideas, the authors have attempted to interpret some of the findings of earlier conceptions research. The framework is also being used to guide development of diagnostic exercises for both paper and pencil and interview questioning. Examples of some of this work is included in this document. In addition, the framework is being used to guide instruction intended to help students differentiate and integrate their initial concepts into a more coherent mechanical theory that can be broadly applied. (TW)

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FINAL REPORT

NIE G 83-0059

INSTRUCTION FOR UNDERSTANDING: A COGNITIVE PROCESS FRAMEWORK

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DECEMBER 29, 1986

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ABSTRACT

The investigators developed a framework within which many of the observations from recent research in beginning physics students' conceptions of forces and motion can be organized. The framework summarizes the mechanisms of force invoked by students in particular situations. It describes the features of physical situations that students believe will modify the relative sizes of forces. Finally, the framework suggests some of the ways students mediate between various forces when predicting or explaining what will happen in a given situation.

Using the framework of students' ideas, the authors have been able to interpret some of the findings of earlier conceptions research. Some problems/situations which seem to involve few variables from the point of view of formal physics involve a great number of salient features from the naive physics student's perspective.

The framework is helping to guide development of diagnostic exercises for both paper and pencil and interview questioning. It is also guiding instruction to help students differentiate and integrate their primative notions into a more coherent mechanical theory that can be applied consistently across a broad domain of contexts.

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FINAL REPORT OF NIE GRANT NO. 83-0059

A SUMMARY AND OVERVIEW

There is a growing body of knowledge about the conceptions of beginning physics students, particularly in the area of mechanics. The primary goal of this research project was to develop a framework for organizing students' ideas about forces. Using data from individual interviews, classroom exercises, and diagnostic tests, we identified ways in which significant numbers of beginning students view the mechanisms of force, modifiers of the magnitude of force, and factors which mediate when more than one force is considered. Using this information we have been able to predict the percentage of students who will give alternative responses to specific questions about mechanics. We can describe the thinking that makes different answers seem plausible to significant numbers of students. The framework is guiding us in further research in students' alternative understandings and in our teaching. We are told that the framework is proving to be useful to researchers at the University of Massachusetts, Amherst and the National Learning Center, Pittsburg.

We developed the framework by looking at the students' notions of forces from two perspectives. The first was to consider the descriptions of novice thinking as viewed from the perspective of formal physics. We developed elaborate concept maps from the perspective of each group. As we were about this work, we did not discover any single theory of mechanics invoked by all novice students. In other words, the students varied in their understanding of the mechanisms and modifiers of forces. When two forces were present, there were different sets of considerations in determining which would be the stronger of the two. This led us to a second way of organizing the framework. Setting formal physics aside, we focussed on the responses and explanations of our students and identified patterns in their thinking.

The present version of the framework captures the salient features of problems/situations and suggests the ways those features will influence students' answers and explanations. For some students, we have been able to predict answers to subsequent questions, but not all students consistently choose the same features which they consider as most critical. Because there are numerous features which students identify as important in situations, the framework helps explain that while the students' answers seem random from the point of view of formal physics, there can be a system to many of their choices.

We obtained feedback from paid consultants at numerous points along the way. Don Finkle, Steve Monk, Dewey Dykstra, and Geof Loftus critiqued the framework in its various forms. Joan Heller interviewed students as part of the evaluation of the validity of the framework. During

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consulting exchanges, we also obtained feedback regarding the framework from the cognitive process psychology group and the physics education group at the University of Washington, the Cognitive Process Research Group at the University of Massachusetts, Amherst, the critical and creative thinking group at the University of Massachusetts, Boston, and the National Learning Center, Pittsburg.

Although the framework and many of the diagnostic questions have been used by others and their data shared with us, for the most part the development and evaluation of the framework was accomplished with data from our students at Mercer Island High School. In the initial stages of development, our introductory physics students and other science students who had not yet enrolled in physics, answered questions on early versions of diagnostic tests. Within the first two weeks of classes for each of the last two years, our diagnostic test and a diagnostic test developed by Clement, et al from the University of Massachusetts, Amherst were administered to all beginning physics students in the classes taught by Minstrell and Stimpson. Pre-instruction quizzes were taken by these students prior to instruction in many of the mechanics units.

The results of some of these tests are included in this report. The individual questions and students' answers are individually consistent with earlier published results of the conceptions research. Since the focus of our research was to seek relationships between various answers, we were more interested in collections of answers to various questions rather than results of an individual item or a single test score. Therefore, most of the analysis was by the specific answer rather than right vs. wrong. The individual responses were correlated with each other. It was from the clusters of similar answers and explanations that we inferred the salient features of the framework.

For five novice physics students, we have data from interviews conducted the spring before they began their physics course. During their year in the program, we collected paper-and-pencil results from their work. It is interesting to note many consistencies between the salient problem features one year and the next, prior to, during, and, in some cases, even after instruction.

This report is organized in two major parts. The first describes and validates the framework. This is a draft of an invited address to the 1987 Winter Meeting of the American Association of Physics Teachers. A subsequent version will be submitted to AAPT as they have expressed an interest in publishing the framework. The second part of the report is a series of very short, loosely connected papers describing various facets of either the research effort or the results of specific activities. These papers provide details of data and relationships referenced in the first section of the report.

DESCRIPTION OF STUDENT THINKING REGARDING THE IDEA OF FORCE

What is their definition of force if they give one?

Virtually all our students have taken both the U Mass Diagnostic and the Mercer Island Diagnostic. The sorts of students' notions described here are inferred from students' answers to questions on these diagnostic tests and from observations reported in the research literature.

For those students for whom we have interviews, there is a place in the interviews wherein we asked students which of the factors they've identified they would classify as a force, why, and how would you define a force/ what does force mean to you?

THE FRAMEWORK

I. MECHANISMS

A. Push/Pull by an outside agent
   1. Action by contact/touching (sometimes called a pressure from contact)
   2. Action by some causal agent through an indirect connection
   3. Action across space
      - empty space or intermediate material?
      - gravity, what is it? differentiated
         - from air pressure
         - different from weight?
         - What are the effects?
         - differentiated from magnetic and electrical?
   4. Actions by passive objects, characteristics or state of objects that can and can't exert forces

B. Force as a Property of an object
   1. Weight
      - makes things fall/ holds things down
      - like inertial mass, holds things back
   2. Motion
      - Force of motion conserves motion
         - constant straight line velocity
         - constant curvilinear motion
         - continued acceleration after active agent removed
   3. Qualities
      - "May the 'force' be with you"
      - Material, like Helium

C. Resistance
   - Directional or nondirectional
   - Holds things down like weight
   - Holds things back like inertial mass
   - Mechanism
      - rubbing
      - ambient medium
      - a property of the system rather than resulting from interaction between objects

II. MODIFIERS OF MAGNITUDE OF FORCE

A. Relative Size of objects involved
The "larger" exerts the greater force
1. Spacially large
2. Heavy/weight
3. Strength

B. Relative Activity of objects
The "more active" object exerts the larger force
1. Motion
2. Effort
3. Internal
material's natural tendency
actions like an engine
will or desire

C. Actions vs. Effects
The object that causes the greater change exerts the greater force
Have students made a distinction between forces exerted and forces felt?
If so, are the magnitudes different?

D. Potential vs Actual Amount
Are students focussing on the amount of force an object could exert or does exert?

III. MEDIATIONS AMONG FORCES

A. When one or more forces are in the same direction, they will explain the motion in that direction.

B. When one or more forces are in the opposite direction
Are the forces, properties of the system, and resistance
resolved one for one?
yielding to which is the most salient factor?

C. When forces are orthoganal,
Does the initial force yield to the second
immediately?
gradually over time?
initially, but then come back?
completely, partially, or not at all?

D. When forces are other than parallel or perpendicular

SO WHAT ARE STUDENTS' INITIAL CONCEPTIONS REGARDING FORCE?

A FRAMEWORK FOR ORGANIZING THE PHENOMENA

At the beginning of a unit on dynamics, the teacher may ask the students what they think of when they think of force. Typically a majority of responses center around "Force is a Push or Pull." Text treatment of dynamics from elementary grades at least through high school begins with the assumption that force is a push or pull. The teacher and the students move on believing there is common understanding about the nature of force. To operate under this and similar assumptions may be contributing to the invocation and persistance of conceptions that stand in the way of students' development of their understanding of dynamics.

This paper suggests that this and other beginning notions of students demonstrate that students' conceptions regarding force are very different from those of formal physics. Students are not blank slates but come with initial ideas, many of which will be useful in dynamics. Their ideas, however, are not clearly differentiated from each other, and they are not integrated into a clear conception of force that is consistent with that of formal physics.

Although many of their ideas are similar to ideas from Aristotle, Impetus Theory, Newton or some other theory existing in the history of the development of physics, we do not find that student thinking in general about dynamics is consistent with only one theory. The particular conceptions we suggest in this paper are those it seems reasonable to us to assume are dominant in a class of beginning students. The thinking of an individual student in many cases is consistent across tasks and may persist through time and even through instruction. While several conceptions have been identified as being used by large proportions of introductory physics students, there does not seem to be one theoretical structure of novice thinking into which they fit.

This paper describes the results of our search for a novice theory related to force and motion. Although no single theory was identified, we infer aspects of a framework within which most of the phenomena of students' conceptions about force and motion can be organized. Rather than a catalog of errors in student thinking from the perspective of formal physics, in our framework we have attempted to describe students' ideas in their own words to contrast their thinking with that of formal physics. The inferences put forth in the paper are based on observations made during our teaching and research and of observations made by other investigators. This paper is not an attempt to review the literature of relevant research but an attempt to organize the phenomena in a rational and useful way. (Note: For a listing of students' conceptions in mechanics, see McDermott, 1984, and Halloun and Hestenes, 1985.)

Within our framework we will first attempt to describe prominent attributes of the students' conceptions regarding force. Then, we will suggest ways in which these conceptions go together to give the results of conceptions research reported by ourselves and others. Finally, (in this or a subsequent article) we present our implications for curriculum and instruction in dynamics toward the formal conception of force.

INITIAL CONCEPTIONS REGARDING FORCES

I. MECHANISMS OF FORCE

Push/Pull-

Initial descriptions of what force means to students usually starts with "a push or pull." Furthur elaboration includes "something that affects something else," and "it causes an effect." So, push or pull, to students, includes actions by touching external agents like hands,springs, etc., but it also includes causal agents indirectly connected to the object of interest. For example, in the situation of a cart on a table, attached to a string that goes over a pulley and is attached to a weight hanging over the end of the table, students will readily suggest that the weight is exerting a force on the cart.(See figure 1.) "It is causing it to move, so it makes a force on it." In a situation with a horse harnessed to a sled towing another sled with boxes stacked on each sled, many students suggest "there is a force by the horse on box A", a box on the top of the stack on the second sled.(Figure 2.) So, for these students since the horse or the weight cause the effect, they are forces, or they exert forces. The influence of these causal agents is not wrong but their conception of force is different from the formal conceptions of forces on the cart or the box.

The push or pull can be an action at a distance, but here again their conception is different from that of formal physics. First, for at least fifteen percent of beginning physics students, gravitational and electrical forces are not well differentiated from magnetism. "The earth has a magnetic pull on the moon. It attracts the moon through electrical charges." "The pull of the earth on the moon is magnetic." Secondly, like early theorists in the history of science, students have trouble with there not being an intervening medium like air to help "pass along the force" in situations involving action at a distance. In fact, for many students it is the pressure of the air that causes an object to weigh something.(Minstrell, 1982)

No Passive Actions-

The students' conception of push or pull does not include the passive actions. (Driver, 1983, and Minstrell,

1981) The table under a book at rest or moving supports the book or resists its tendency to fall, but that passive action is not considered a force. A string connecting a moving object to a causal agent is not considered to be pulling on the object.(Figure 3.) The string is just a passive intermediate. Anything which is not seen to stretch, compress, or otherwise move and demonstrate effect is just there to resist or restrict the motion of something, but it doesn't exert force.

Properties-

In addition to considering force as an action by an outside agent, beginning students often consider the properties of the object as forces, perhaps because they are factors that affect the situation. One of the most common properties of an object considered to be a force is the motion of the object. The faster the object is traveling, the more force it is considered to "have." This preconception has been a research topic reported in the research literature. It is very persistent. The "force of motion" may exist in different forms. It may be responsible for keeping the object moving with uniform motion in a straight line.(Gunstone, 1985, Hewson, 1986, Minstrell, 1984, and Vienott, 1979) It may be the forward force that conserves curvilinear motion.(McCloskey et. al., 1980) Or, it may be the force that causes the vertical acceleration (of a ball thrown upward, for example) to keep on accelerating. For example, many students believe the maximum velocity of the ball will be well after the ball left the hand, perhaps when it is halfway to the top, "until the downward force of gravity can wear it down."(Clement, 1982)

Other "internal" properties of the object are sometimes considered to be a force. Materials out of which objects are made may be considered a force because they are relevant factors in the situation. For example, the balloon may rise because of the "force of the helium." An engine of a car is exerting a force on the car from the novices point of view, probably because it is such a salient feature and cause for the car moving. Also, for some students the will of the person or animal is a force on the person or animal, again possibly because it is a cause for the person moving.

Resistance-

Friction is a term that students use to represent resistance to moving objects. It is sometimes viewed as coming about through a rubbing action, but usually it is just seen as a property of systems that tends to retard motion. For some students it does so by holding the object back, but for many friction resists motion by holding things down. For other students there is no implied direction to friction. It's just there resisting motion. The following is from a session at the end of the school year wherein Minstrell was interviewing an entire class about their changes in understanding from the beginning of the year:

Student 1: Another thing that I didn't know was that the force of friction had a direction.
Minstrell: You mean initially?
S 1: You know.. that there is a direction to that force and it's opposite to the motion of that object.
M: What convinced you that there was a directionality to the force of friction?
S 1: Well it had to do with equal and opposite forces and the experiments we did. What would happen and why?
M: Okay. How was your idea about friction different when you came in? If it wasn't directional, what was your idea?
S 2: I just thought it was there, I didn't know but when you push the block this way, you see that ..then you have a frictional force that has to be like that (opposite)...
S 3: For lack of anything to say about friction I thought it was something like the floor sucking on whatever it was.
S 4: What I was thinking is that it would have a certain amount of friction to it. Like a 400 pound box would have a certain amount of friction to it. It would take, like if a guy was pushing on it, the force of friction would be greater on the box.
M: So for any given box or something, there's a certain amount of friction associated with that box?
S 4: Yes. That's what I was thinking.
M: A potential amount of friction?
S 4: Right.

II. MODIFIERS OF MAGNITUDE OF FORCE

Another aspect of the meaning of force to beginning students is the way they decide the magnitudes of forces acting on an object or the relative magnitudes of the "action-reaction" forces during the interaction between objects.

Size/Strength-

The size of the objects involved affect the magnitudes of the forces. Larger objects are responsible for larger forces. This idea has a sound basis, larger objects usually can exert larger forces on an object than can smaller objects. However, this evidence seems to be generalized to "larger must exert larger forces." Although size can sometimes mean spatially large, more often it is described in terms of the weight of the object. When blocks are stacked up with the heaviest block (A) on top, "since A has the greater weight, it is exerting the greater force." and "because B has less weight and cannot exert as much force as A..." are common explanations. In another question wherein the larger object, the Washington Monument, is below the smaller object, a mosquito, some students suggest the monument exerts the greater force because "the monument's mass is greater than the mosquito's." In a situation involving a bowling ball hitting a pin, many students say "..the bowling ball has more weight, so it hits the pin with more force than the pin hits the ball with..."

For many students relative "size" has to do with strength. When two magnets interact with each other, the stronger magnet exerts the greater force. This is so compelling that even when the strong and weak magnets are both attached to opposite ends of a cart, "the stronger magnet has a greater force" is used by a large proportion of the students to explain why they believe the cart will move. When two different "strength" springs are attached to each other and the opposite ends each held by one's two hands, many students suggest one hand will feel more force because "the spring is stiffer, thus creating a greater outward force when compressed." When two people lean against each other, many students suggest that Sam, the stronger person, will exert the greater force.(See Figure 4.)

Activity-

Another salient feature of problems/situations involves the relative activity of the objects involved. The principle invoked seems to be, the "more active" an object is, the more force it exerts. Activity is our word within our framework, but it seems to be associated with situations involving motion, muscular effort, or internal activity like the engine of a car or sometimes possibly even the effects of the will or desire of the persons involved. For example, in a situation where a moving car hits an identical stationary car, "the stationary car has no force at that time..", and "Since the one car is moving, it's exerting the greater force..." When two people of equal weight sit opposite each other in office chairs with rollers and person A extends her legs with her feet on B's chair, "A exerts a bigger force because A actually does the motion." In a similar situation with two skaters facing each other with hands touching each other's, whichever one extended her arms (causing the backward motion) was the one exerting the larger force, even if their masses were different.

The idea that passive objects cannot exert forces, described earlier, relates to this activity continuum. While some students only apply the principle that more active objects exert greater forces, some carry the idea far enough to claim that without activity there is no force. For example, in the situation of the moving car colliding with the identical stationary car, "The one car is at a standstill, so it can't exert a force." When confronted with a lamp at rest on the floor, some say "The floor does not move to exert a force."

Know Forces by Effects-

For many students the way to know about actions is to monitor the effects. Generally this idea sounds good from the standpoint of formal physics as well. But, beginning students are more general in their use of the idea. If, as in the case of the book on the table, one can't see the table move, "then the table can't be exerting a force." When the two identical cars collide, the one that "feels" the greater force will be the one that will be most changed, either in terms of movement or damage. In a pillow fight the pillow will experience a greater force than the persons head, "because the pillow is soft and it will be stopped by the head."

Potential vs. Actual Force-

Frequently students answer questions about relative magnitudes of forces on the basis of the amount of force the object could exert rather than the force it does exert. With the book on the table, some will say the table exerts the larger force, justifying their response on the basis of it being heavier or stronger. "It would take a lot more than one book to break the table." In ca[illegible] where friction could possibly have an effect it is often considered to exert the maximum force even in situations where the book is at rest on the level table with no sideways forces.

III. MEDIATIONS AMONG FORCES

Forces in the same direction-

When all the forces involved in the situation are in one direction, the object(s) will move, accelerating or with constant velocity, in the direction of the force(s). For example, when an object is falling, the major force on it is in the down direction, so the object moves downward. When a car moves along and collides with the stationary car, all the force appears to be in the direction of movement, so the system moves in that direction.

Forces in opposite directions-

In situations where forces involved are in opposite directions, if they are perceived to be comparably salient, forces in opposite directions will compensate for each other one for one. For example, when two people lean against each other, some students explain this by compensating forces, "Sam is stronger, but Shirley exerts more effort, so they both stay there."(See Figure 4.) If one force is determined to be particularly salient, it may overcome the others and the object will do what it does because of that overwhelming force. In the situation of the bowling ball colliding with the bowling pin, the bowling ball exerts the larger force because, "It is heavier, plus it is moving."

Forces orthogonal to each other-

Results here depend on which of the forces is perceived to be stronger and whether one or another force is believed to be strong initially and gradually worn away or weak initially and gradually getting stronger. An object initially moving horizontally keeps on moving horizontally until gravity gradually takes over and "overcomes the sideways motion." In some cases the initial force appears so strong that the additional force is of no consequence and therefore does not change the motion of the object. For example, the object rolling along the path on the top of a table requires a hit in the direction that one wants the object to go if one wants it to change direction.(See Figure 5.) In other cases the second force appears so strong that the object no longer has any vestiges of the original force/motion. Often one is perceived as the stronger force initially, but it gradually gives way to the more sustaining force, like the force of motion gradually giving way to the weight or friction or whatever it is that holds things down to the surface.

Forces other than parallel or perpendicular to each other-
These tend to affect situations in much the same way that the perpendicular forces do. (See Figure 6.)

PUTTING THEM ALL TOGETHER TO EXPLAIN OBSERVED MOTIONS

In this section we will consider a few examples which will put together the Mechanisms, Modifiers, and Mediations to explain some of the more elaborate problems from the conceptions research. One reason that it has appeared that students do not reason consistently is that different students see different features as salient in the problems. Thus there are various answers/explanations given by novices to the same problem situation depending upon the features to which they attend.

Consider two people leaning on each other and staying stationary.(See Figure 4.) Some students suggest that Sam who is stronger and heavier exerts the greater force. Others suggest that Shirley exerts the greater force because she exerts the greater effort. Still others answer suggesting they exert equal and opposite forces on each other, some justifying that answer with rationale that says Sam is stronger but Shirley exerts more effort to compensate for Sam's strength. Thus they get the keyed answer but for reasons that involve their novice principles of heavier exerts more force and more active exerts more force.

Consider an automobile wherein the driver puts her foot down to a certain position of the throttle pedal. The car tends to speed up at first, but then it tops out at some velocity and stays at that velocity. So, a constant force at first causes the object to speed up and then sustains its motion. It would appear students are sometimes saying that a constant force can explain both the accelerating case and the constant velocity case. From the point of view of many

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students this is what happens and it does so because during the first bit of time the force is an action that gets the car going. Then the car "has" that force. During the next bit of time the additional force adds more velocity to what it had, so it is now moving faster. It will keep speeding up until it reaches the speed that is just right for that force on that car. Then, that is the force of motion that will just sustain the constant velocity. If one turns off the engine, the larger force of motion will gradually be overcome by the weight (or the friction) of the car and it will slow down to a stop.

Consider the ball thrown vertically. Explanations seem to differ. Some say the ball was moving fastest when it left the hand and after that the force of motion gets whittled away by gravity. Others suggest that the object keeps on accelerating upward after it leaves the hand until it gets about half way to the top. Then gravity begins whittling away. In either case there is a conserved motion in the upward direction that gradually gives way to gravity and eventually the object comes down.

Consider a projectile thrown horizontally. The object is believed to travel out horizontally at first with vertical gravity, or the downward tending weight of the projectile, gradually taking over until the object falls vertically. Throwing the object with twice the horizontal velocity will keep it up longer; it has twice as much force. For many it will "hang" for twice the time before hitting the floor. But, if an object of twice the weight had the original velocity, it would hit in less time, usually in half the time, because the double weight will pull it down proportionately faster. Consistent with this is if the students are pressed to consider the situation of the object with twice the weight having twice the original velocity in the horizontal direction, this object is predicted to hit the floor in the same time as the original projectile by those who gave the neatly proportional answers for the fast case and for the heavy case. Other predictions depend on how strongly invoked each of the principles were.

Consider the soccer players downfall. With the motion of the ball crossways to the goal, there is the tendency to kick or otherwise hit the ball with the hit in the direction of the opening between the goalie and the post. Novice physics students explain that this hit, if it is hard enough, will completely overcome the force of motion of the incoming ball.

Consider the object in circular motion. When the inward force is cut off, students will frequently predict that the object will continue in curvilinear motion. This explanation is dominated by a conservation of motion, whatever motion it had when it was released. Others will predict the ball will gradually veer outward from the tangential path. These students seem to be invoking a conservation of the tangential motion gradually yielding to the "outward force of motion."

In the past we have constructed test questions to learn whether students understand a specific concept of formal physics. By varying pertinent information, we expected appropriate variations in student responses. Often the changes in their answers seemed random, not related to the changes we had made. Exploring the explanations given in support of their answers, we have learned that there are a variety of features in the test questions which physicists believe are irrelevant, but students describe as salient. While it appeared that students were randomly answering the questions we had posed, it was often the case that they were influenced by features which had meaning to them. By listing these features in our framework and recognizing ways in which the students believe that they affect a given situation, much of the students' reasoning can be seen to be systematic and consistent. By grouping problems according to features viewed relevent by beginning physics students, rather than by features deemed significant by physicists, we have come to see clearer patterns in student responses.

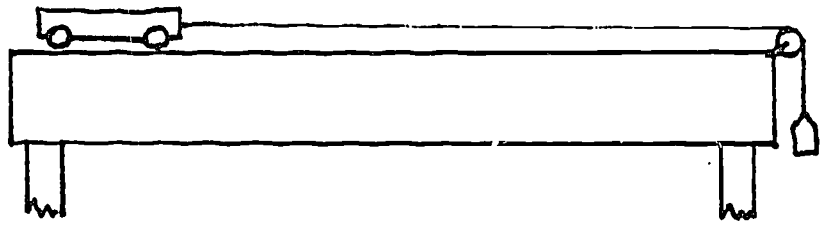

Figure 1.

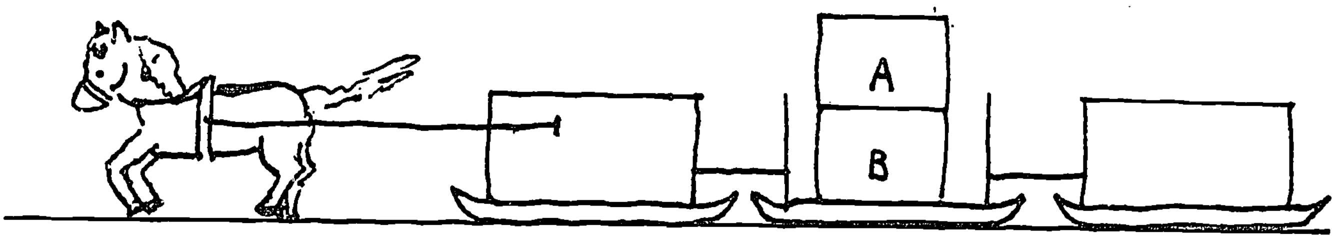

Figure 2.

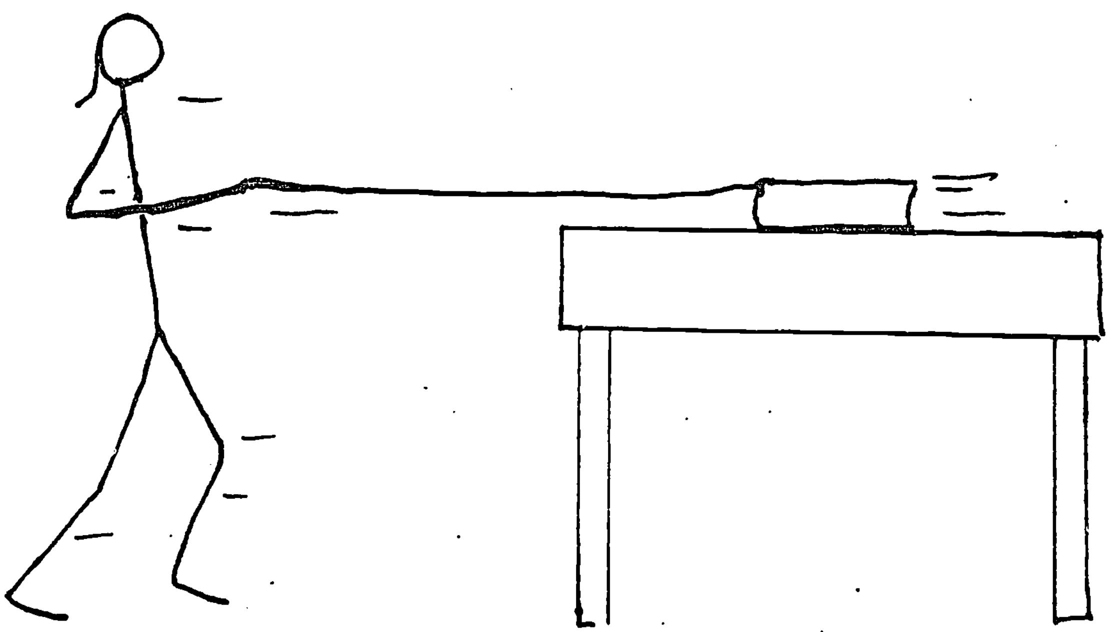

Figure 3.

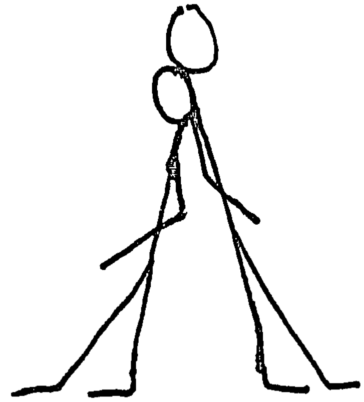

Figure 4. SHIRLEY SAM

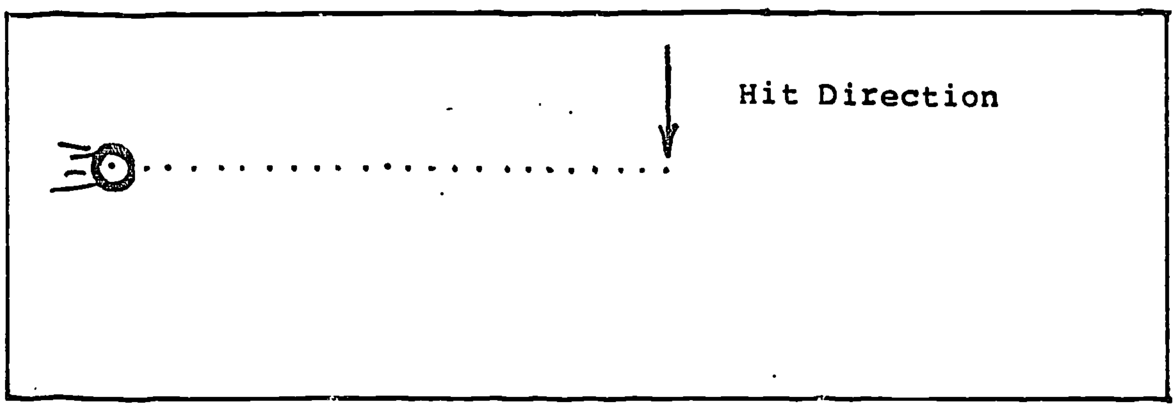

Figure 5.

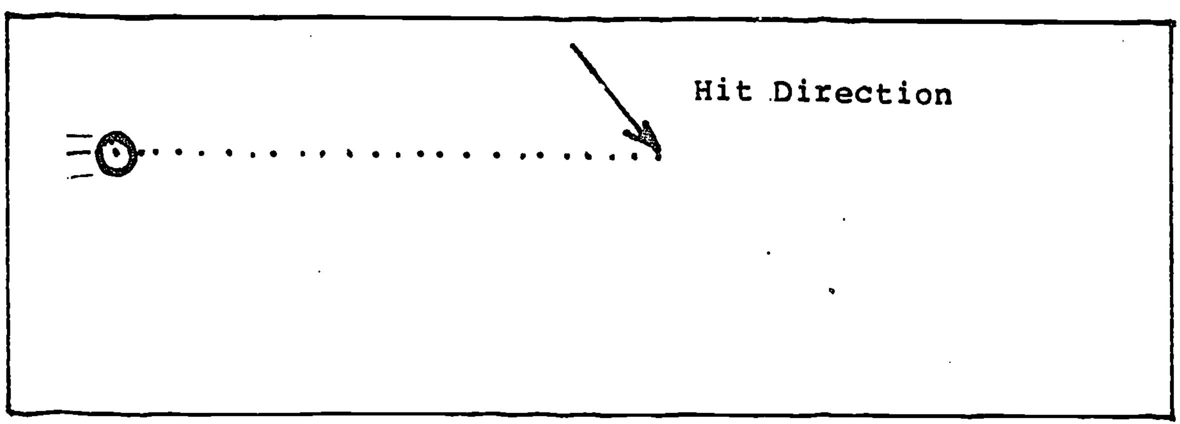

Figure 6.

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INTERVIEWS BY JOAN HELLER

Analyzed by Jim Minstrell

In May of 1985, Joan Heller, then a psychologist at UC Berkeley, came to Mercer Island High School as a consultant to our research project. Over a period of three days she interviewed thirteen students to provide possible validation data for our framework.

The focus of this aspect of our project was the testing of a framework for beginning physics students' understanding of the concept of force. Under the assumption that student thinking should be quite different after a study of mechanics compared with the thinking before class work, Dr. Heller was presented with students from three groups. There were five students who had indicated they would take physics the following year (novices), four students who were completing a year of study under Minstrell, and four who were completing a year of physics under another teacher at Mercer Island High School. The students from the different groups were interviewed by Heller in a scrambled order, and she did not know from which group each had come. Minstrell's instruction differed from the other teacher in that Minstrell specifically had addressed students' initial conceptions while the other teacher emphasized the formal ideas in the traditional manner of a strong PSSC teacher. Each of the students had been identified by their science teachers as a very strong, articulate student.

It is interesting to note that Heller was able to correctly place most of the students on the basis of her interviews. She correctly identified three of Minstrell's students. The fourth she knew had had some experience but wasn't sure in which class she belonged. Heller correctly identified another three students plus the fourth student from Minstrell's class as students who had developed some formal notions of physics. The remaining six she identified as probably naive students. One was a 4.0 GPA student from the other physics classes. The other five were correctly identified as "pre-physics" students.

In this section of the report we will first use the framework to describe the thinking of one of the students about the idea of force, as an example of the sort of data accumulated during the interviews. Then, we will briefly describe inferences about some stages of development in students' thinking about the force idea as a result of encountering the formal ideas in the instructional setting.

Each student was asked more or less the same series of questions about the same problem situation. The problem, one used earlier by Heller at UC Berkeley, involved a horse harnessed to a sled which was connected by rope to a second sled which was connected to a third. On the middle sled were two boxes, box A stacked on top of box B (see figure 1). During the interview the students were first asked to

ID________________________

DATE______________________

Boxes in Sled

A horse pulls three sleds behind it, as indicated in the diagram. Two boxes, A and B, are stacked on top of each other in the middle sled. There is friction between boxes A and B, and also between box B and the floor of the sled. There is also some friction between the bottom of the sled and the surface beneath it.

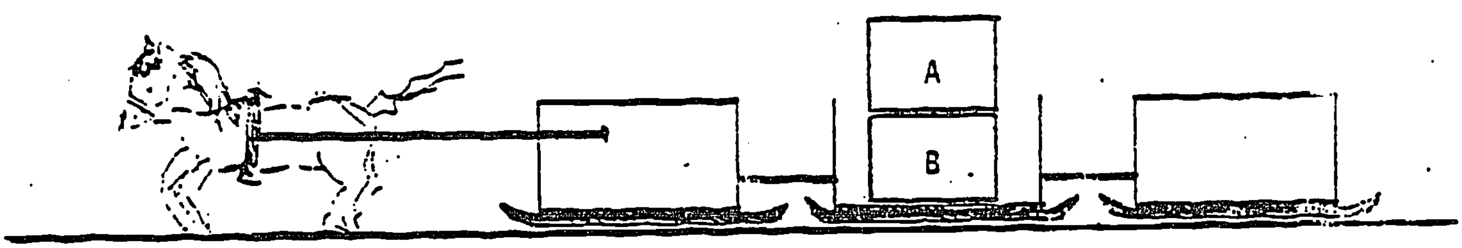


Figure 1.

give a general description of the situation. They were asked how the situation would be different if the system were accelerating vs. constant velocity. Next, they were asked about the factors affecting the motion of box A under the assumption of a constant velocity. As a next level of detail, they were asked to distinguish the properties of A from the outside influences on A. Usually by now the student had used the term force, so the next level of questioning about the same situation asked specifically which factors, properties, or outside influences the student considered to be forces acting on A. These latter three levels generated most of the information on the students' conceptions of force. They were asked to draw force diagrams for the constant velocity and constant acceleration cases. Finally they were asked about various variables as to their potential effects and explanations, e.g. constant velocity vs. constant acceleration, fast vs. slow, what if the harness broke, how would weight of A affect it, height of A, compare rigidities of B, what if all the air were removed, and other variables that happened to come up.

I. Beginning Students' Ideas about Forces

In this section we will use the framework to organize the ideas of a student as exhibited through transcriptions of her tape recorded interview. Although the extent to which the framework was validated as a model of student thinking is questionable, it did serve to help organize the ideas exhibited by the students during the interviews. That serves as some validation of the utility of the framework as an organization of phenomena.

Interview number 12--female, pre-physics

Definition of Force-

This student's definition of force centers around "something that had its own strength, like with the wind or the horse..They have their own strength. ..Or the weight or ..design. ..since they're all affecting the course of things,.. I would call them all forces..the strength of the horse, the strength of the pull, the weight of the boxes."

The student had some formal knowledge about the nature of weight or gravity but it was of questionable value. When confronted with the idealization of removing the air from the situation, the student suggested that gravity would no longer be a factor.

Interviewer: You put the whole thing under a dome and you give the horse an oxygen mask and then pump out all the air. All right, so you make a vacuum.

Student: Okay.

I: ..What would happen that would be different, if anything if there's no air?

S: Oh I've heard something about weight not making any difference then, maybe less resistance, maybe.

I don't know. Maybe the friction or you know, I was talking about these little molecules of air, maybe there wouldn't be that friction, there'd probably be some other kind of friction, but there wouldn't be that friction. Oh gravity. I don't think there'd be any gravity.

I: Anything else? Okay. You said you heard something about weight not making any difference.

S: Yeah in a vacuum.. This guy was standing on top of this fortress and he dropped off a cannonball and a feather or something like that. And they were supposed to go down at the same time.

I: This is in a vacuum? Oh weight doesn't make a difference. They'll fall at the same speed?

S: Yeah... That never made sense to me though, because I never understood it was in a vacuum until recently. I think or maybe I still don't understand it. Because it always seemed to me like heavy things fell faster..so it must be in a vacuum.

Thus, the formalisms didn't seem to make much sense to her.

Her conception of force doesn't include forces by passive objects.

I: Another thing it (box A) could do is go down, why isn't it going downward?

S: Well B is in the way and the ground is in the way and the sled's in the way.

We get additional confirmation of this when later she is talking about the forces acting on box B. "B would have all the same ones but A on top of it also." She then draws the downward force of A on B but neither A nor B has an upward force drawn to represent a force by an object below. The objects below are "just in the way."

She suggests that friction keeps the box A from falling off, but draws friction acting in a downward direction, and says "it would be scrunched down...I guess not knowing much about it, but friction, there'd be a constant down movement and maybe up too.. just holding it there." When asked if friction was vertical, somehow holding it down and together, she responded, "I guess."

S: "Yeah I suppose so, because it doesn't seem to work normally."

The student's conception of weight was mixed. On the one hand weight brought things down, but there was a strong conception of weight as inertial mass and weight as a force that holds the object back, like "the drag of the weight," whereupon she draws it as a force in the backward direction.

S: The drag of the weight.

I: There's some sense of it being held back. By its own tendency not to move or something?

S: Yeah I guess it's why the horse has to pull it cause it's pulling some...resistance...

So in summary of the student's conception of the forces acting on the box, "its got drag over here (the weight of the object holding it back) and the pull over here (the horse as the causal agent indirectly through the sleds connected to the box), and friction down here (holding the object down)", and there is no passive upward force by the box below A.

From these interviews we learned quite a bit about the students' mechanisms of force. We did not learn much about their modifiers of the magnitude or the mediations among forces.

II. Development of the Conception of Force

The following are inferences about the development of students' ideas about force derived as a result of Heller's series of interviews.

Themes in MIHS Interview Data-

<u>Direct vs. Indirect Interaction</u>

1. Force as any influence, including properties of the system and surrounding systems.

(discrimination required to achieve next level)

2. Force as an active influence that causes motion (properties influence forces).

(generalization required)

3. Force as active or passive influence that maintains position or causes motion.

(generalization required)

4. Force as "direct" interaction (through contact or action at a distance).

<u>Relationship between Force and Motion</u>

1. There must exist an "active" influence to maintain motion (no clear notion of force in scientific terms).

A constant pull for constant speed
A greater pull for greater speed
An increasing pull for increasing speed
No pull for no motion.

(discrimination required)

2. Forces cause motion.

A constant force for constant speed
A greater force for a greater speed
An increasing force for increasing speed
No force for no motion.

(discrimination required)

3. A net unbalanced force gets related to acceleration.

A constant force produces a constant acceleration
A greater force produces a greater acceleration
A decreasing force produces a constant speed
No force for no motion.

(discrimination required)

4. A net force is related to acceleration and no net force gets related to no acceleration (the object continues with the motion it had when the net force became balanced.

A constant force produces a constant acceleration

A greater net force for a greater acceleration
A balanced force for a continued state of motion
once the object is in motion
Balanced forces for no motion.

<u>Relationship between Weight, Friction, and Force in General</u>

1. A greater weight requires a greater pull, regardless of friction. Weight and friction are independent (they have separate effects). Friction is a property of the system.
(discrimination required)

2. A greater weight requires a greater pulling force regardless of friction. Weight is considered an inertial force, holding the object back. Friction, like glue, holds things down.
(discrimination required)

3. Transition state: Greater weight requires a greater force only if there is friction (unless the weight is so great it overrides friction). Weight increases friction. Friction becomes a lateral action by something through rubbing.
(discrimination required)

4. Friction force is a function of the normal force. A greater normal force requires a greater pull to overcome friction. If no friction, then no effect of the weight. Friction is a force parallel to the surface. The inertial mass of the object is separated from the object's weight. The greater the mass the less the acceleration for a given pull.

DYNAMICS DIAGNOSTIC

TESTS AND RESULTS

Mercer Island High School

To test our hypothesized framework and as a source of data for revision of the framework, we developed diagnostic test questions to be administered to high school students prior to their taking physics. Our diagnostic tests were attempts to sample students' understanding of several facets of motion. Some questions focussed on their knowledge of phenomena in natural situations, while others were to draw out the students' conceptions used to explain phenomena. In 1985 we administered a Dynamics Diagnostic to 89 beginning physics students while the 1986 version was taken by 132 physics students. Other groups of students from other classes responded to the additional questions. Here we will report only the results from the questions administered to the beginning physics students.

In this section we present the 1986 version of the Dynamics Diagnostic first with the results and interpretation. For two classes the test was administered during the first week of school. Since the other three classes did not take the test until approximately one month into the school year, when results from the two groups differ, we will describe the differences. In a few cases the questions would be expected to be sensitive to early instruction. Also, when there are interesting differences between the results on the 1985 version and the 1986 Dynamics Diagnostic, those are reported.

It should be noted that many of these questions are not so well polished that students can clearly answer the question without some interpretation and clarification of the situation on the part of the test administrator. Therefore, on the 1986 version we asked for students' explantions for their choices. Also, the administrator talked students through any of the question situations that were in any way identified by the students as ambiguous.

THE TEST, RESULTS, AND BRIEF INTERPRETATIONS

1. Between 15% and 25% of our introductory students do not distinguish between kinds of action at a distance, e.g. gravity and magnetism.

1. A. "You could talk about the pull of the earth on the moon
25% as a magnetic, a gravitational, or an electrical pull. They all mean the same; they're just different words."

B. "No, they are all different. A magnetic pull is
75% different from a gravity pull."

Do you agree with A or B? Explain why.

2. The relative strengths of interacting objects affect the relative forces they exert on each other.

2. A huge strong magnet and a tiny weak magnet are brought near each other. Which of the following statements makes the most sense to you?

a) The huge magnet exerts no force on the small one which exerts no force on the large one.

85% b) The huge magnet exerts more force on the small magnet than the small one exerts on the large one.

*16% c) The huge magnet exerts the same force on the small as the small exerts on the large.

1% d) The huge magnet exerts less force on the small magnet than the small does on the large.

1% e) The huge magnet exerts no force on the small magnet which exerts force on the large one.

Briefly explain your choice.

3. The results for this item were likely affected by instruction. In the two classes which took the test the first week of class 25% of the students predicted the heavier object would fall faster, and that is consistent with results from other novice groups. For the other seventy-five students who took the test after some study of kinematics there were only two students who predicted the heavier would fall faster. A common belief is that weight affects time of fall.

3. When a lead ball and a wood ball of the same size are dropped from the same height of about two meters...

13% a) the lead ball gets to the floor way before the wood ball does.

87% b) the two balls get there about the same time.

c) the lead ball gets there way after the wood ball.

4. The force of gravity is different from weight for many students. Gravity is considered a kind of force. After instruction students who see that things fall equally fast suggest it is because the force of gravity is the same on them.

4. From the previous situation the force of gravity on the lead ball is...

17% a) way more than on the wood ball.

82% b) the same as on the wood ball.

2% c) way less than on the wood ball.

*Percentages may not total 100% due to some students giving multiple answers.

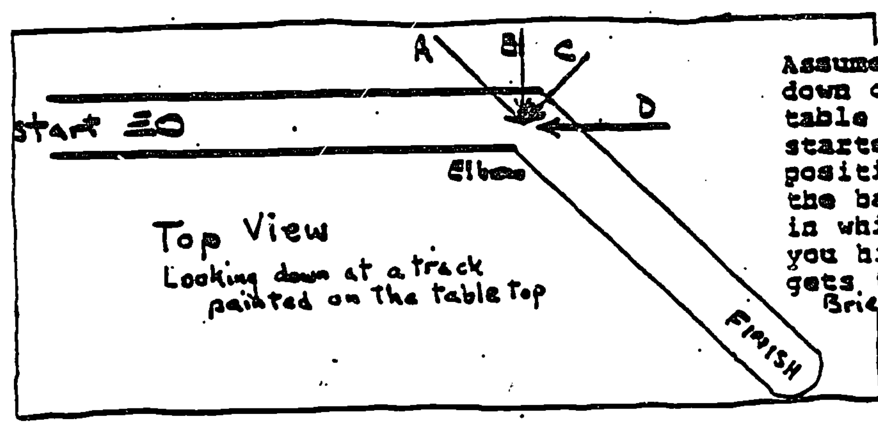
5. The weight of an object and/or the force of gravity on that object may be affected by air pressure. For a significant portion of our classes a large change in the air pressure greatly changes the weight of an object.

5. Suppose an object weighs 10 lb when weighed in our classroom. If we can create a room wherein we can increase the air pressure to twice what it was in our classroom, what would be the weight of the object in that special room? Briefly explain.

5lbs (10%), 10^- (8%), 10 (43%), 10^+ (10%), 20 (29%)

6. Because there are two main forces involved, from the beginning students' thinking the force of motion will dominate until the force of the hit takes over in the direction of the target. This point of view is probably even more prevalent than the results of this question suggest. If the particular situation is in the realm of experience of the student, they will answer on the basis of recognized experience. If not experiential, they will likely resort to their dominant belief based on the salient features of the problem.

6.

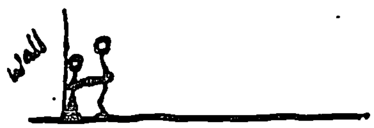


Assume you are looking down on a track on a table top. A ball is started from the START position. If you want the ball to end at FINISH in which direction would you hit the ball when it gets to the elbow? Briefly explain

A (50%), B(46%), C (5%), D (2%)

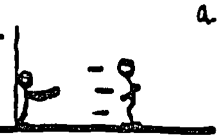
7. Relative activity of people (or inanimate objects) involved in an interaction suggest the relative magnitudes of forces exerted on each other. For many, passive objects cannot exert forces.

7. Who exerts a force on whom in each situation below? and How do you decide? If both exert forces, which is larger?



86% girl
6% woman
8% both

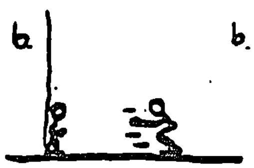
a.



a. The girl is the one who extends her arms.
Who exerts the force?
Reasoning:

10% girl
74% woman
16% both

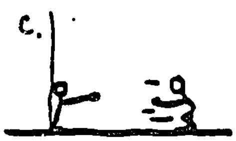
b.



b. The woman is the one who extends her arms.
Who exerts the force?
Reasoning:

13% girl
7% woman
80% both

c.



c. Both extend their arms.
Who exerts the force?
Reasoning:

8a. Objects, or in this case a person, perceived to "cause" the resulting change in a system exert forces on the system. Thus, the person, even though not touching the object, is said by many students to be exerting a force on the book.

8b. For many students passive things like strings cannot exert forces.

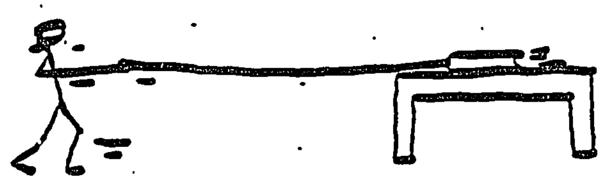
8c. Passive objects like tables don't exert forces. Only about one third of the students suggested that the table exerted an upward force.

8d. Air tends to exert a downward force on objects. Air pressure is responsible for weight or gravity.

8e. Gravity affects things in the downward direction.

8f. While many students can recognize situations wherein friction is involved, only about a third of them suggest that friction acts in a direction counter to the direction of motion of the one surface tending to move over another.

8g. Only about half the students believe weight represents a downward force on the object in this situation. To many others weight just keeps the object from moving. It is a factor affecting the state of motion of things, but is not a force. For others it is a force in the backward direction.

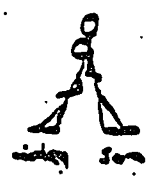


8. A person pulls on a string (as per the picture above) and the book moves toward her.
a) Which one or more of the following would you say is (are) exerting a force on the book?
b) For each one that is exerting a force on the book, describe the direction(s) of the force if there is a direction.

	(a) Yes	or no	(b) Direction: up	down	left	right	other (describe)	no direction
* the person?	80%	20%			94%	1%	3%	
the string?	80%	20%		3%	88%	3%	5%	1%
the table?	70%	30%	49%	6%	2%	7%	16%	17%
the air?	68%	32%	17%	57%	21%	28%	5%	17%
gravity?	95%	5%	2%	97%	1%	1%		1%
friction?	94%	6%	8%	6%	17%	34%	23%	20%
the weight of the book?	75%	25%	3%	70%	5%	9%	7%	7%

* Direction Percentages are percent of those who said, "Yes, there is a force."

9. This tends to be a very complex problem from which to predict responses. Heaviness and strength are stated dominant features, but the perceived necessary activity of the smaller person to keep the situation at rest also guides the thinking of many students.



9. Sam is stronger and heavier than Shirley. They lean on each other (as per the picture.)
Which seems to make the most sense?
a) Sam exerts a greater force on Shirley
b) Sam and Shirley exert equal forces on each other.
c) Shirley exerts a greater force on Sam.
d) Neither exerts a force on the other.
Briefly explain.

A (50%), B (29%), C (21%)

10. This problem was to help separate heaviness from strength. Generally students assume heaviness and strength are correlated with size. The fact that these responses are so different suggests that the weight was a very salient feature of problem 9.

10. Suppose Sam is stronger but not heavier than Shirley. Under these conditions which of those answers would make the most sense?
a, b, c, d, (circle one)
Briefly explain.

A (16%), B(70%), C (9%), D (2%)

11. Force for many students is associated with anything that has its own strength and can move. Our instruction in kinematics apparently reduced the percentages of students who held this belief. The classes that took the test at the beginning of the year included about 20% suggesting this belief, and that is consistent with our results during previous years. In the three classes which had had instruction in kinematics for a month, there were only about 3% who limited the force idea on this problem. This is one small piece of evidence in favor of the hypothesis that knowledge is integrated between areas rather than isolated individual strands.

11. Forces can only be exerted by
1% a) people or other animals.
11% b) anything that can move.
88% c) anything.

12. A large proportion of beginning physics students explain constant velocity motion with extra force in the forward direction. Some believe the force must come from an outside action while others think of force as a motion property of the object.

12. Given that object A is moving toward the right with a constant velocity (constant speed in a straight line). Which of the following makes the most sense?

86% a) Object A has more forward force on it than backward force.
9% b) Object A has equal forward and backward forces on it.
5% c) Object A has less forward force on it than backward force.

Briefly explain how you decided.

13. The first year we asked this question we expected the same results as with problem 12. This problem, however, has the additional feature that the object is now moving twice as fast as in the previous problem. For many students this now elicits a need to also account for the aditional feature of the change in velocity. Often their explanations include a mix of force as a property of the object and force as an action on the body. Thus, for some it has the same extra force it had for the original motion plus something to account for the change.

13. Suppose the object from the previous problem had twice the velocity.
Which of the following would make the most sense?

72% a) the extra force forward would be twice as great.
8% b) the extra force forward would be the same as in the previous problem.
7% c) the forward nd backward forces would be equal to each other.
4% d) the extra backward force would be the same as in the previous problem.
7% e) the extra backward force would be twice what it was in the previous problem.

Briefly explain.

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14. The results of this problem were affected by instruction for three of the classes. Typically about 75% of our beginning students predict that an object moving horizontally will not fall as rapidly as the same object dropped. In general their explanations involve a mediation between the force of motion which the object has in the beginning and the weight or force of gravity which gradually takes over.

14. A ball falls from the end of a table and takes 1/2 second from the edge of the table to the floor. Another identical ball rolls across the table at a high speed and then off the table.
From the edge of the table to the floor it will take

20% a) more than 1/2 second.
72% b) 1/2 second, no difference.
8% c) less than 1/2 second.

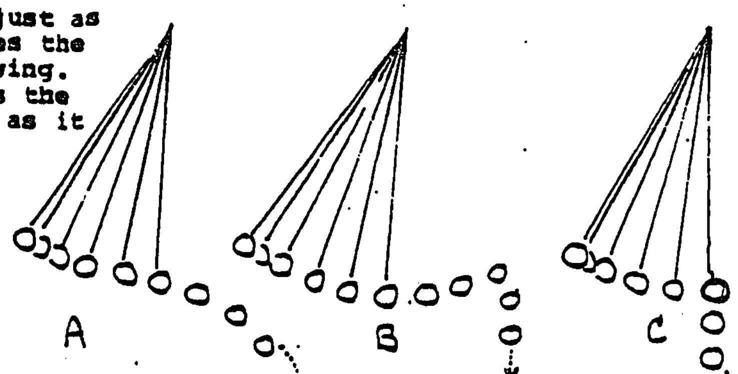
Briefly explain.

ADDITIONAL QUESTIONS, RESULTS, AND BRIEF INTERPRETATIONS

Pendulum- (n=89)

The trouble with this problem is that all the answers involve the same student explanation: First the object has the force of motion, then gravity or the weight takes over. For answer C the weight takes over immediately upon cutting the string. In A it takes over gradually. While in B, the motion is conserved for a bit until the weight overcomes it.

The string breaks just as the pendulum reaches the mid-point of the swing. Which diagram shows the path of the weight as it falls?
Briefly explain how you decided.

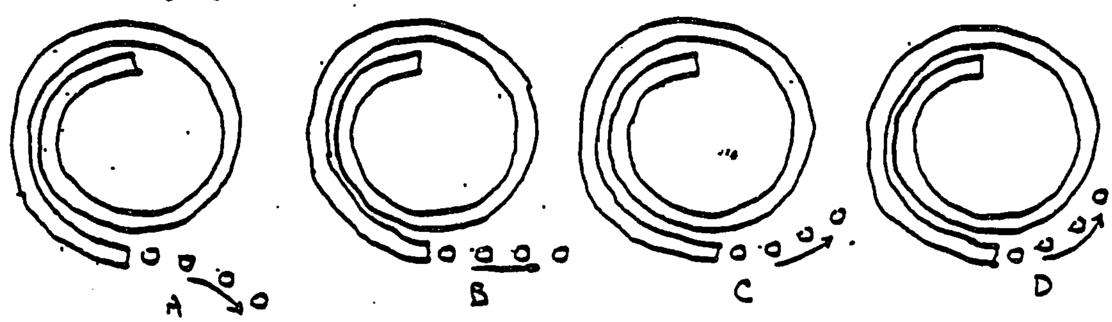


79% 9% 12%

Tube- (n=89)

This problem involves conservation of motion with a possible mediation later. In A the motion is conserved but then the centrifugal force gradually takes over and the ball curves outward. B involves conservation of linear motion, and D involves conservation of curvilinear motion. C begins with conservation of the curvilinear motion, but then gravity takes over as the object runs out of curvilinear motion.

Imagine you are looking down at a spiral tube lying flat on the ground. A ball enters the tube. Assuming there is no air resistance, which path does the ball follow upon emerging from the tube?



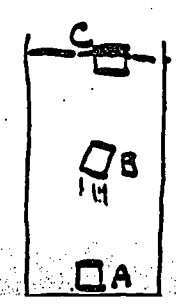
Explain how you decided.

A (15%), B (61%), C (24%)

Floater- (n=89)

Nearly 70% of the beginning students hypothesized that the object exerted a force on itself. Usually this was in the form of a property of the object, e.g. the force of its density or the force of the wood or the air. Their conception of force involves factors that might cause the object to do what it does.

17. A block of wood is held down near the bottom of a container of water at position A. It is released and rises to the surface to point C. On the way, while it is rising it passes through point B. Explain, what are the forces involved to cause it to be rising as it passes point B?



SCIENCE DIAGNOSTIC

TESTS AND RESULTS

University of Massachusetts

As a further test of the validity of our inferred framework, we used the framework to interpret the results of data being generated by the John Clement and the Cognitive Process Research Group at the University of Massachusetts, Amherst. Among other products of their research grant is the development of a Science Diagnostic to test students' ideas about interactions between objects and about friction. The test provides rich data about students' conceptions of force. Since their project goals held a large intersection with ours, we've been collaborating during the last three years. In 1985 we administered their Diagnostic to nearly one hundred students, and in 1986 a slightly modified version of their Science Diagnostic was administered to one hundred and forty-five students at Mercer Island High School.

In this section of our report we present the latter version of the test, the results with our students, and our interpretation of those results from the viewpoint of our framework. Our version of their test has one more question, Stock Cars Too, an extension of their Stock Cars. The purpose of that extra question was to investigate the students' distinction between forces experienced by and forces exerted by objects. A second major difference is that we did not include a confidence scale with each question as they did. Finally, we asked students briefly to explain their choice of answer for each question. We felt these variations better served our research purposes by focussing on students' ideas and experience or rationale in support of those ideas.

PLEASE NOTE: Their Science Diagnostic is not yet published. Do not cite these results or use these test questions without first consulting John Clement, Cognitive Process Research Group, Physics Department, University of Massachusetts, Amherst, Mass. 01003.

THE TEST, RESULTS, AND BRIEF INTERPRETATIONS

Lamp

A large proportion of introductory physics students do not believe passive objects like floors exert forces.

LAMP PROBLEM

Jim buys a new floor lamp and leaves it standing in the corner of his room. Which of the following do you think is true?

22% ___1) The floor exerts an upward force on the floor lamp.

78% ___2) The floor does not exert an upward force on the floor lamp.

Briefly explain.

Stock Cars

Objects experiences force differently, perhaps based on how much damage the student believes the object will sustain. Stationary cars are passive, while moving cars are active, so the stationary car will expereince more force (effect).

STOCK CARS

At a demolition derby, one stock car weighing 2000 lbs. runs head-on at 20 MPH. into another identical stock car which is standing still.

When they collide:

21% ___1) Each car experiences a force, but the moving car experiences a greater force

59% ___2) Each car experiences a force, but the stationary car experiences a greater force

19% ___3) Both cars experience the same size force

___4) Only the moving car experiences a force

___5) Only the stationary car experiences a force

___6) Neither car experiences a force

Briefly explain.

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Stock Cars Too

Active (moving) objects can exert more force. Passive objects can't exert forces.

STOCK CARS TOO

Consider the same situation as above.
When they collide:

59%__1) Each car exerts a force, but the moving car exerts a greater force
4%__2) Each car exerts a force, but the stationary car exerts a greater force
7%__3) Both cars exert the same force
30%__4) Only the moving car exerts a force
__5) Only the stationary car exerts a force
__6) Neither car exerts a force

Briefly explain.

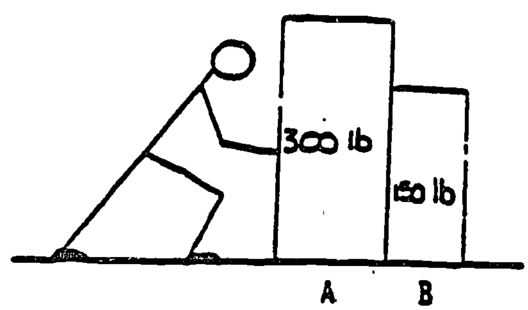
Stationary Boxes

This is a complicated problem from the standpoint of the framework of student thinking because it involves many salient features which conflict with each other and make prediction/explanation difficult. An active human is pushing a heavy box which was moving but is now at rest against a lighter box which has been passive all along, but which is now somehow preventing any further movement of anything in that direction. Answers are very scattered. A, the larger of the two boxes, is dominant to 36% of the students, while B, the one that is seen to prevent any further movement si supported by 25%. 12% suggest that only the "active" box could exert a force, while 14% suggest that neither of the boxes which are seen as passive can exert forces.

STATIONARY BOXES

A warehouse worker is strong enough to slide a large box A up against a smaller box B. He then tries to move both boxes at once as shown in the picture, but he is not strong enough and nothing moves.

Think about whether A exerts a force on B and whether B exerts a force on A while he is pushing but unable to move them. Which one of the following is true?



36%__1) Each exerts a force on the other, but A exerts a larger force

25%__2) Each exerts a force, but B exerts a larger force

9%__3) Each exerts a force, and these forces are the same size

12%__4) Only box A exerts a force

2%__5) Only box B exerts a force

14%__6) Neither box exerts a force on the other

Briefly explain.

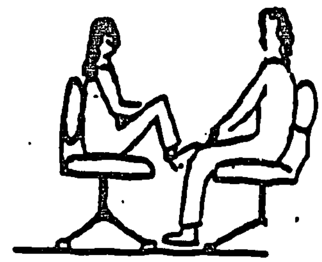
Office Chairs

41% of the students chose to say that A, the physically active person, exerts the greater force. 31% suggest that the passive person can't exert force.

OFFICE CHAIRS

Two students who both weigh 120 lbs. sit in identical rolling office chairs facing each other. Student A places his bare feet on student B's knees, as shown below.

When student A kicks outward, B moves to the right. What happens to A?



89% ___1) A moves left (<----)

4% ___2) A moves right (---->)

8% ___3) A remains motionless

Briefly explain.

Think about whether A exerts a force on B and whether B exerts a force on A when A kicks outward. Which one of the following is true?

41% ___1) Each exerts a force on the other, but A exerts a larger force

11% ___2) Each exerts a force, but B exerts a larger force

15% ___3) Each exerts a force, and these forces are the same size

31% ___4) Only A exerts a force

2% ___5) Only B exerts a force

___6) Neither exerts a force on the other

Briefly explain

Handsprings

A significant proportion (57% here) of the students believe that stronger things will exert greater forces.

HANDSPRINGS

As shown in the diagram below, you are holding two springs, a strong, stiff one and a weak, soft one, between your hands. You move your hands a few inches closer together, compressing the springs a bit against each other. When you hold your hands still in this position with the springs somewhat compressed, which one is true?

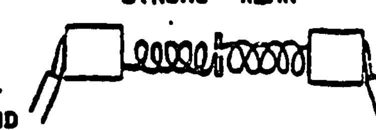
45% ___1) The left hand feels a greater outward force

12% ___2) The right hand feels a greater outward force

35% ___3) Each hand feels a force of the same size

1% ___4) Neither hand feels a force

___5) Other (Explain)



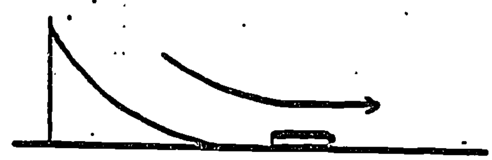
Briefly explain.

Suitcase Problem

For many students friction is just a property of the system and is not exerted in any particular direction. For objects to slide to a stop requires the weight of the object to overcome the motion, suggested here by over a quarter of the students.

SUITCASE PROBLEM

A suitcase slides from a ramp onto the steel floor of the baggage area at an airport. While it is still sliding on the floor, which one of the following sentences explains why the suitcase stops?



4% ___1) The floor pulls down on the suitcase, causing it to stop.

36% ___2) There is a frictional resistance to the motion of the suitcase, but it is not in any particular direction.

27% ___3) The floor does not exert a force on the suitcase which affects its motion, but the weight of the suitcase pushes down against the floor.

7% ___4) The floor exerts a force on the suitcase in the direction opposite to the suitcase's motion causing it to stop.

30% ___5) Other (explain).

Briefly explain.

Steel Blocks

Things on top of other things can exert larger forces because they have their weight actively working for them. To the extreme, 38% suggest only the active object on top can exert force. The passive object below cannot exert force.

STEEL BLOCKS

A large steel block weighing 200 lbs. rests on a small steel block weighing 40 lbs. as shown below. Think about whether A exerts a force on B and whether B exerts a force on A. Which is true?

38% ___1) Each exerts a force on the other, but A exerts a larger force

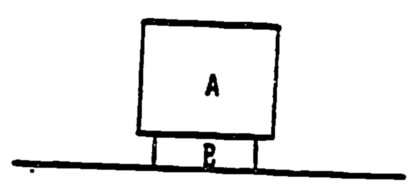
8% ___2) Each exerts a force, but B exerts a larger force

12% ___3) Each exerts a force, and these forces are the same size

38% ___4) Only block A exerts a force

1% ___5) Only block B exerts a force.

2% ___6) Neither block exerts a force on the other



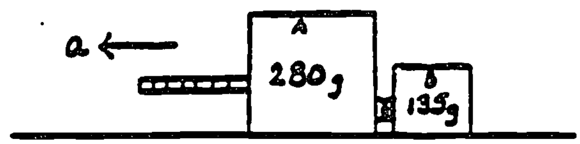
Briefly explain.

Pulling Blocks Problem

This is another problem that involves so many salient features in conflict that it is difficult to predict/explain the outcome. In the first problem the larger and heavier object is in the front and probably seen by some to be actively pulling. Others see that neither of these blocks is the active puller. It is something out of the picture in each case. In either case there is also the last object lagging behind and holding things back due to its weight. This is particularly dominant in the second problem where the heavier object is the one being towed by everything else. In the second problem apparently 30% believe the first block is the active one doing the pulling.

PULLING BLOCKS PROBLEM

Two blocks are hooked together and pulled by a rope on a horizontal surface. The rope pulls the blocks so that they accelerate.
Think about whether each block, A or B, is exerting a larger force on the other block, or whether the forces they exert on each other are equal.
Which one below is true?



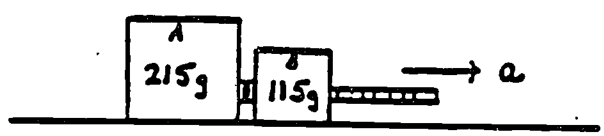
66% ___ 1) A exerts a larger force

18% ___ 2) B exerts a larger force

18% ___ 3) The forces are equal

Briefly explain.

In the next case below two different blocks are being accelerated to the right.
Which one below is true?



56% ___ 1) A exerts a larger force

30% ___ 2) B exerts a larger force

14% ___ 3) The forces are equal

Briefly explain.

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Crates

Of those students who did not believe friction was a force in the problem, 61% suggested the heavier object, the one that seems to dissallow motion, exerts the larger force. For those for whom friction was a force, the friction force was larger than that of the person (presumably in either case because the human could not overcome the crate.)

CRATE PROBLEM

A man tries to push a crate weighing 400 lbs, but he cannot move it. While is pushing to the right:

Is friction one of the forces acting on the crate in this situation?

16% ___NO

84% ___YES

If you said no above, think about whether the block exerts a force on the man while he is pushing.

1% ___ The block exerts a force on the man

3% ___ The block does not exert a force on the man, it's just in the way.

2% ___ The block exerts a force on the man that is equal to his pushing force.

10% ___ The block exerts a force on the man that is larger than his pushing force.

1% ___ The block exerts a force on the man that is smaller than his pushing force.

If you said Yes above, which is larger, the force of the man pushing, or the force of frictio on the crate?

68% ___ The friction force is larger

8% ___ The force of the man pushing is larger

6% ___ These forces are the same size

Briefly explain your choices.

Bowler

This problem is interesting because it is so easy to predict/explain on the basis of the framework. All the important factors (size, weight, motion, hardness) predict the ball will exert the larger force. For those who are strong in the belief that passive objects cant exert forces, only the ball can exert a force. Because this problem is so unidirectionally predictive, it or one like it makes a strong question for measuring the effectiveness of instruction.

BOWLER

When a bowling ball weighing 16 lbs. hits a bowling pin weighing 4 lbs.:

77% ___1) Each exerts a force on the other, but the ball exerts a larger force

1% ___2) Each exerts a force, but the pin exerts a larger force

1% ___3) Each exerts a force, and these forces are the same size

___4) Only the pin exerts a force

20% ___5) Only the ball exerts a force

___6) Neither exerts a force on the other

Briefly explain

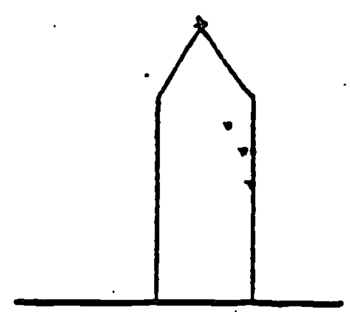
Mosquito

This problem suggests mixed features. The heavy object is below, but the active object is above. The heavy object is passive and to many it can't exert force.

MOSQUITO

On a day with no wind, a mosquito lands on top of the Washington Monument.

Think about whether the mosquito exerts a force on the monument and whether the monument exerts a force on the mosquito while it is resting there. Which of the following is true?



15% ___1) Each exerts a force on the other, but the mosquito exerts a larger force

18% ___2) Each exerts a force, but the monument exerts a larger force

16% ___3) Each exerts a force, and the forces are the same size

4% ___4) Only the monument is exerting a force

41% ___5) Only the mosquito is exerting a force

8% ___6) Neither exerts a force on the other

Briefly explain.

Magnets

55% of the students suggest it will move, most because the stronger object will exert the greater force.

MAGNETS

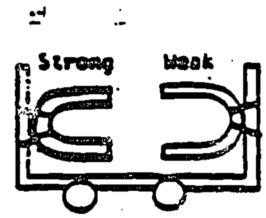
Two magnets are securely fastened to opposite sides of a cart, and aligned so as to repel each other, as shown in the diagram. The cart is sturdy so the repulsion between the magnets cannot break the cart sides.

If one magnet is much stronger than the other, and we place the magnets as shown in the diagram so that they push away from each other, what will happen to the cart?

28% ___1) It will move left (<----)

28% ___2) It will move right (---->)

45% ___3) It will remain motionless



Briefly explain.

Book Pile Problem

Again in this problem friction is considered a property of the situation or system. If friction does have a direction, it is downward to keep the object from moving sideways.

BOOK PILE PROBLEM

Twenty large books are stacked in a pile in Roger's garage, and Roger wants to read the black one in the middle. He tries to pull it horizontally out of the pile without taking the books above it off, but can't move it.

This is primarily because:

38% ___1) There is a frictional force exerted in a downward direction on the book from the one above it.

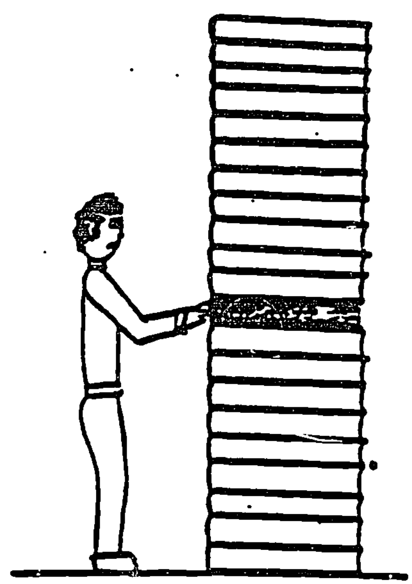
14% ___2) There are frictional forces acting horizontally on the book.

2% ___3) The book's inertia opposes Roger's pulling force.

7% ___4) Gravity pulls down on the book

16% ___5) Roger exerts the only force on the book, but the book is trapped because of the number of books on top of it.

22% ___6) Other (explain).



Briefly explain.

Three Boxes

The dominant feature here is that A is on top and so has its weight which can be actively used to push down. C is just passively at rest under B, and for many passive objects can't exert force.

THREE BOXES

Three boxes are stacked on top of each other with the lightest on the bottom and the heaviest on the top. Think about whether the top and bottom blocks A and C exert a force on the middle block B. Which is true?

33% ___1) Both A and C exert a force on B, and the force A exerts is greater

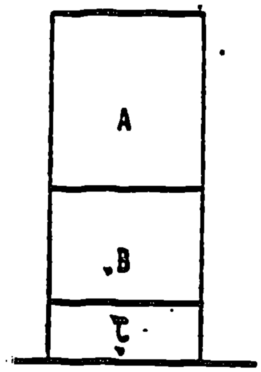
16% ___2) Both A and C exert a force on B, and the force C exerts is greater

10% ___3) Both A and C exert a force of the same size on B

39% ___4) A exerts a force on B, but C does not

1% ___5) C exerts a force on B, but A does not

1% ___6) Neither A nor C exert a force on B



Briefly explain.

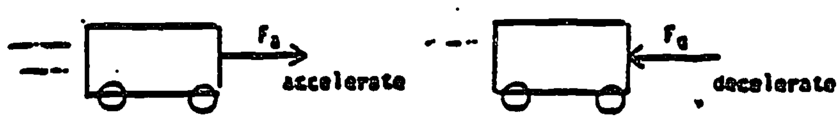
Speeding Up and Slowing Down

A dominant feature is that once the object is actively moving, a larger force will need to be exerted to overcome the force of motion.

SPEEDING UP AND SLOWING DOWN

0 ---> 5 mph

5 ---> 0 mph



Consider the force F_a needed to accelerate (speed up) a cart from 0 mph to 5 mph in a 10 second period. Compare it with the force F_d needed to decelerate (slow down) the same cart from 5 mph to rest in the same 10 second period. Neglecting friction, compare the sizes of the two forces. Which is true?

16% ___1) The size F_a is greater than F_d because it must overcome inertia.

43% ___2) The size of F_a equals the size of F_d

32% ___3) The size of F_d is greater because it must overcome momentum.

2% 4) Other (please explain)

Briefly explain

CORRELATIONS

So far the majority of the described data has been answers for individual test questions. We know quite a bit about the specific answers students give for specific questions, problems, or situations. Is there any relationship between the specific answers, or are they random responses to questions as they occur? We believe students conceptual reasoning is not random. While we do not belive we have identified a theory of student reasoning, we have data to suggest that students' alternative conceptions are persistent, and their use of their conceptions is more systematic than than they've been given credit for in the past.

We began our search for relationships between facets of students' reasoning by correlating all the items within each diagnostic test, pre-instruction quiz, The Lawson Classroom Test of Formal Operations, and some items on the semester final exam with each other. In many cases, we had combined several questions that were related from our formal point of view, e.g. situations dealing with action reaction (Newton's Third Law). These yielded interesting results, but not the number or types of relationships we expected. We now believe that was largely because we were analyzing their thinking from a formal physics viewpoint.

Later we gradually changed to a more fine grained analysis. We correlated each possible answer to each item of the diagnostic tests with every other possible answer on the other questions. At this level we bagan to see more consistency in the sorts of answers/explanations they were giving. This allowed us to redevelop our framework to more closely reflect students' wording and, we believe, students' thinking. The data gathered during the last year was analyzed at this level of analysis. With our framework applied at this level of detail we could better predict how students collectively and sometimes individually would respond to questions.

The persistance of students'ideas

Consider student number 7 (S7), who was interviewed by Heller in the spring prior to S7 taking physics. During the interview while relating the forces acting on box A she said, ".. probably air pressure, just pushing down on A and B and everything else... air pressure, it's a force from above instead of a force pulling on it." Later in the interview when she was asked what would happen if all the air were removed, she responded with ".. there would be a greater tendency for A or any of it to just start floating." Thus, during the interview at least, she exhibited a strong belief that air pressure perhaps along with gravity caused things to weigh something.

On the Dynamics Diagnostic given the first week of physics class, S7 responded to a question regarding an object which weighed 10 lb under normal atmospheric conditions. When placed in a special room wherein the air pressure could be doubled, she suggested the object would now weigh 20 lb. "It would weigh two times as much because the air pressure on it is twice as great, causing it to push down harder on the scale."

At the beginning of a unit on the nature of gravity and its effects, the students were asked what would happen to the weight of a 10 lb object which was placed under a glass dome, and the air was evacuated from under the dome. She suggested it would weigh less than 10 lb, and explained "probably a little of the weight is due to air presure, so by removing the air pressure, probably a little bit of weight will be removed." Then, during this brief instructional unit, an object was weighed in air and then under a Bell Jar with the air removed, allowing students to see that there wasn't a detectable change in the weight.

Finally, at the end of the school year the same diagnostic question was used with the special room wherein the air pressure was doubled. S7 said, "20 lb., because the object will be pressed twice as hard down on the scale.

This student's idea associating weight with air pressure apparently had not changed over the course of the year. Lest the reader believe this must be a very dull student, let me hasten to interject, she is a National Merit Scholar, and will graduate in the top of her class. That the instruction failed is clear, even when teachers knew the difficulties that some students would have, and specifically designed class demonstrations, problems, etc. to address those difficulties. We view this as one of the many examples we have of students' ideas persisting reasonably consistently across time and even through instruction. Just on the air pressure/ weight difficulty alone, it is interesting to note that the set of all students who exhibited that confusion at the end of the year was a proper subset of the people who had the confusion at the beginning of the year.

Consistent systematic reasoning across tasks

Consider the idea that passive objects do not exert forces. Consider the Bowler Problem on the U Mass Diagnostic Test. One of the answers suggests, "Only the ball exerts a force." Bowler (5) was chosen because the problem had many features to which students might attend. Those who picked (5) were most likely inclined toward "passive objects don't exert forces." We identified all the students who gave that answer and then looked at other problems that clearly have a "passive objects don't exert forces" answer. For the two classes analyzed 100% of those students also answered the Lamp Problem with answer 2, "The floor does not exert an upward force on the floor lamp." 83% answered Stock Cars Too with 4, "Only the moving car exerts a force." 100% of those students answer Office

Chairs with "Only A exerts a force." 82% answer Steel Blocks with 4, "Only block A exerts a force." 91% answer Mosquito with either "Only the mosquito is exerting a force." or "Neither exerts a force on the other." 73% answer Three Boxes with "A exerts a force on B, but C does not." In each of these cases, the majority of these students answer the problems with an answer that suggests the passive object does not exert a force. Only the active object exerts a force. It would appear that these students are quite consistent in their conceptual reasoning across tasks.

So much for predictions within a particular group that had responded to one item in a particular way. What happens if we run correlations between Bowler (5) and these predicted answers across our entire group of one hundred and forty- five students? Bowler is correlated with each of these predicted answers at statistically significant levels ($p<.01$). R values for Bowler (5) with Lamp(2) was .26, with Stock Cars Too(4) was .19, with Chairs(4) was .63, with Steel Blocks(4) was .25, with Mosquito(5) was .36, and with Three Boxes(4) was .34. Bowler (5) was not positively correlated at a statistically significant level with any other items on the test.

These predicted observations and statistical analyses suggest that the conceptual notion that passive objects don't exert forces is consistently invoked by beginning students as they try to explain physical situations. While we still may not be able to predict what a given student will do, we are now better able to predict how groups of students will behave on a particular question or set of questions. Students are fairly consistent in their conceptual reasoning across tasks, if we are able to identify their conceptual thread of relationship.

DISSEMINATION ACTIVITIES

During the course of this project we've taken advantage of opportunities to influence science and mathematics teaching, curriculum development, teacher training, and learning research at the local, state and national levels. In each of these situations, we shared the perspectives of this research project in one form or another.

Publications resulting from the project include the following:

Teaching for the Development of Understanding of Ideas: Forces on Moving Objects, in 1984 AETS Yearbook

Constructing New Ideas About the World: Toward Establishing a Newtonian Point of View, submitted with Dewey Dykstra to The Journal of College Science Teaching

Constructing New Conceptual Understanding in the Classroom, prepared for the Festschrift for The International Commission on Physics Education

Students Beliefs in Mechanics: Cognitive Process Frameworks, in the Proceedings for the Fifth Conference on Reasoning and Higher Education, Boise State Univewrsity.

A Position Paper on Instructional Needs Regarding Understanding and Problem Solving in Physics, prepared for the Conference on The Psychology of Physics Problem Solving: Theory and Practice, Bank Street College, NY.

Presentations and workshops specifically disseminating the results of the frameworks research were conducted at the following:

The Project for Critical and Creative Thinking, University of Massachusetts, Boston.

The National Learning Center, The University of Pittsburg, Pittsburg.

The Cognitive Process Research Group, The University of Massachusetts, Amherst.

The Conference on Reasoning and Higher Education, Boise State University.

The Summer Institute for Mathematics Teachers, The University of Washington.

The Spokane School District Physics Teachers, Spokane, Washington.

The Puget Sound Area Physics Teachers, at the University of Washington.

The research will be presented in an invited address to The American Association of Physics Teachers, San Francisco in January of 1987 and to the Northwest Washington Physics Teachers in March of 1987.

Other publications and presentations relating to the frameworks research are being negotiated.

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