SRRI #248

Classroom Teaching Experiments in Mechanics

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Introduction

In this paper we report on a classroom teaching experiment examining two units on the topics of gravity (3-4 lessons) and inertia (4-6 lessons), taught in two successive years. In the first year's evaluation neither unit appeared to be more effective than control class instruction. This reinforced our impression that it is very difficult to help students achieve significant conceptual change in areas where deep-seated preconceptions conflict with instruction. Major revisions were made by a group of teachers and researchers during the subsequent summer. In the second year, the gravity and inertia lessons achieved high gains relative to control classes. In this report, we propose possible reasons for the significant gains in the second year.

Quantitative Results

Method

In order to get some indication of student's conceptions before and after introduction, we used multiple choice pre- and post-test-results. The pre-test was given at the beginning of the school year, and the identical post-test was given near the end of the school year (a separation of 7 months). Depending on when units were taught, the post-test measured retention over periods of 2 to 4 months. The conceptional questions were designed by the researchers in the project, and both control and experimental teachers were kept blind to the contents of the test. Although parts of the test were revised for the second year, a core of identical questions in each area was retained to enable comparisons between the year on identical questions.

In Duit, R., Goldberg, F., &
Niedderer, H. (Eds.) RESEARCH IN PHYSICS
LEARNING: THEORETICAL ISSUES AND
EMPIRICAL STUDIES. IPN/Inst. for Science
Education: Kiel, Germany. 1992

Diagnostic Results Indicating Conceptional Difficulties

By developing a diagnostic test and giving it to physics classes in control schools, we found evidence for a number of widespread and persistent alternative conceptions in the areas of gravity and inertia. The following examples indicate that many students are unable to answer comparatively simple conceptual questions in these areas, even *after* a full year of traditional instruction in high school physics.

Examples indicating conceptual difficulties with gravity

To a question about a pebble falling to the ground, only 35 % of the students answered that the pebble is exerting an upward force on the earth before it lands (up 8 % from the pre-test). Only 35 % indicated that increasing air pressure would not increase an object's weight (up 12 % from the pretest). Furthermore, only 33 % indicated that decreasing the rotation speed of Mars would not affect its gravitational pull. Perhaps most surprising is the result that only 29 % indicated that the force of gravity would be greater on a lead ball than on a wooden ball of the same size (down 4 % from the pre-test). This question was preceded by a question about falling rates of the two balls, and most students answering equal fallings rates on this question said that the force of gravity is equal on the two balls.

Examples indicating conceptual difficulties with inertia

Students also had great difficulties with inertia concepts after traditional instruction. For example, only 19 % indicated that a hockey puck would be as difficult to accelerate horizontally on the moon as on earth (up from 13 % on the pretest.) Only 34 % indicated that a package of marshmallows that was equally difficult to accelerate in space as a piece of lead would weigh the same on earth (up from 23 % on the pretest.) These data indicate that there are persistent qualitative difficulties in these areas which are difficult to address.

General Strategies Used in All Lessons

Both the original and subsequent revisions of units attempted to draw out students' alternative conceptions and promote explicit discussions of them in the classroom. This was done by asking students their opinion about target problems and delaying giving the teacher's point of view long enough to promote discussion.

The units also attempted to draw out students' usable intuitions by using anchoring examples (for which most students' answers agreed with the current scientific view) and contrasting these to their intuitions about the target problems in discussion. Several demonstrations were also used which were designed to challenge predictions made using alternative conceptions. The lessons were developed by a team of high school teachers and researchers consisting of David Brown, Charles Camp, John Clement, Kimberly Gonzales, John Kudukey, James Minstrell, Klaus Schultz, Melvin Steinberg, and Valerie Veneman. (For detailed descriptions of each of the final units, see the Appendix).

Results

Following are pre, post, and gain scores (percentages) for the two areas for the second year of lesson trials. Because of round-off, gain scores may not be exactly the difference between post scores and pre scores.

Experimental n = 132 / Control n = 79

GRAVITY (5 questions)

	Pre	Post	Gain
Experimental	28	69	41
Control	23	37	13

Pooled within groups standard deviation for gain scores = 29
Comparison of gain scores: $t = 6.676$ $p < .001$

INERTIA (5 questions)

	Pre	Post	Gain
Experimental	19	66	48
Control	17	32	14

Pooled within groups standard deviation for gain scores = 27
Comparison of gain scores: $t = 8.706$ $p < .001$

The above results were more difficult to achieve than we expected. In fact, in the first year we measured no significant gains over controls in these areas. The very small pre-post gains for the first year's experimental group demonstrated the persistence of alternative conceptions in these areas even in the face of instruction specifically designed to deal with them. Perhaps this persistence is not so surprising given the precedent of Newton: the inertial mass concept was apparently one of the most elusive concepts for Newton to invent, and this was one of the very last obstacles he overcame before writing the *Principia* (Steinberg, Brown, and Clement, 1990). However, experience with the first year's lesson trials also gave us a basis from which to rewrite the lessons for the second year.

Hypotheses Concerning Sources of Improvement

In the following we discuss three overall factors that we have reason to believe may have contributed to the increased effectiveness of the second year lessons: (1) As our team gained a more detailed understanding of the "conceptual territory" in these areas, it allowed us to design more "conceptually focused" examples which dealt with specific difficulties; (2) Each unit was split into two sections separated by weeks allowing for "revisiting" of topics; (3) Many more occasions where students give oral or written explanations were included.

Method

The data used to form hypotheses about why the second year's lessons gave better results come from three sources: students' feedback (e.g. written explanations on quiz questions and a questionnaire asking them to indicate which lesson sections were most interesting and helpful); observations of the classes; and feedback from teachers. The student data enable us to assess the students' subjective reactions to the lessons as well as the extent to which the majority of students achieved the objectives at the time of the lessons. In combination with the observation and teacher feedback data, this allowed us to propose strong points and criticisms of the lessons. The best single source of hypotheses for why students achieved larger gains in year 2 is the criticisms of year 1 lessons that were dealt with in the lesson changes for year 2. Our conclusions will thus be grounded hypotheses about the relative effectiveness of specific instructional techniques in the second year.

Conceptual Focus Improved: Overview

Many improvements resulted from a finer comprehension and articulation (on the part of the lesson designers and teachers) of (1) students' entry concepts (alternative conceptions, initial subdomains of experience used, and elusive conceptual distinctions); and (2) the consequent image (by contrast) of the expert's conceptual map.

Our first cluster of hypotheses regarding the apparent increase in effectiveness is: our improved understanding of students' conceptual difficulties encouraged us to select better instructional examples explicitly focusing on these difficulties. This cluster involves several sub-hypotheses so we will begin with an overview. We refer to them collectively as improving the "conceptual focus" of the lessons.

In the summer curriculum development session between the two lesson trials, we realized that our "conceptual maps" of the knowledge in the domains needed to be enriched and concretized, moving away from abstract conceptions such as, *"Objects resist acceleration because of an internal property called inertia,"* to more specific and approachable conceptions, such as, *"When friction is minimized, once they are set in motion, objects on earth tend to keep moving - the heavier they are, the more they have this keeps going tendency"* (keeps going tendency in space was dealt with in a separate lesson).

We refer to the "keeps going tendency" as an "intermediate conception" (intermediate between naive and expert conceptions) because it is a step toward the expert's conception, but it is still not as elegant and general as the expert's conception.

As another example, the original units were structured to focus on the concept of mass as a property of objects by focusing on such questions as whether a puck is "heavy" because of something inside or outside the puck (this was the first question asked in one of the older lessons). Similarly, one of the first questions in another lesson dealt with the equality of forces between the earth and the moon. By contrast, the new units initially shied away from such abstractions by focusing on more familiar, concrete situations, such as pushing a skateboarder.

Thus, the second year lessons recognized more specific conceptual difficulties and dealt with them explicitly and in more depth, whereas the first year lessons were structured in a more standard fashion to deal with elegant, overarching ideas rather than the individual conceptual difficulties. In other words, the older lessons were organized with the goal of portraying the abstract structure of the expert's conceptions, whereas the lessons in the newer version were organized primarily in terms of the goal of engaging and then building gradually on the students' conceptions.

Specific Changes in the Inertia Lesson Making it more Conceptually Focused

a. Recognition of natural subdomains and improved ordering of lesson elements

In the original lesson, the inertial mass concept was developed for objects in interstellar space, then applied to the problem of equal falling rates (the planet earth pulling on small objects), and finally applied to pushes accelerating objects on earth. We criticized this design as moving from the unfamiliar domain to the most familiar, instead of starting with the familiar. We also noticed that some students who learned about the inertia concept for the objects on earth domain still had trouble applying the concept to the outer space domain. Part of the problem was that we hadn't even *recognized* these as three different subdomains, because they are all part of the same valid domain of application (the universe) of the inertia concept from the physicist's point of view. The second year's lesson moved in the opposite direction by starting from examples of inertia in the more familiar domain of pushing objects on earth. Thus, in the second version, a conscious attempt was made to deal with the same alternative conception in several different subdomains and take up the subdomains in order of difficulty.

b. Recognizing more specific conceptual difficulties

In reviewing the inertia lesson structure, we developed two "maps" in addition to the lesson plan: a map of the conceptions or domain knowledge we were attempting to teach, and a contrasting map of the student's initial conceptions. On the basis of observations from the first year's trials, and with the help of Jim Minstrell's observations of his students in Seattle, it was noted that there were several possible sources of confusion that we were not dealing with adequately, shown in Table 1. These were added to our map of students' initial conceptions. Several of these confusions were not addressed in version one of the lesson. Some are phrased in terms of the "keep going" aspect of inertia (e.g., of a runaway train car) or the "holdback" tendency (e.g., of a stationary train car).

Confounding the "holdback" aspect of inertia with friction as sources of (resistance to acceleration)
Confounding the "keeps going" aspect (resistance to deceleration) with the gravity in downward motion (Holdback and keeps going tendencies are part of a single inertia concept for the physicist but appear to be applied to separate subdomains of experience-for the student)
Confounding the "holdback" aspect of inertia with gravity as sources of resistance to horizontal acceleration
Confounding the force of friction with gravity as a force deterring horizontal motion
Confounding mass and weight

Table 1: Sources of confusion about inertia: concept differentiation problems

c. *Increased use of concrete examples and qualitative laboratories*

To deal with these criticisms, we began the second lesson with a *qualitative laboratory* experience dealing with students accelerating and decelerating each other on skateboards, using spring scales as force meters. The students collected a minimal amount of quantitative data but had to give many written answers to questions like, "Why is the skateboard harder to stop with a more massive person on it?" In contrast to most laboratories that are often used as a place to apply what one has just learned in lecture, here we used the laboratory to *introduce* concepts and conceptual problems to the student. One of the most important goals of the laboratory was to set up an extended discussion of qualitative issues in the classroom the next day. Thus, lesson version two used this lab as an extended concrete example to provide a *starting point* for the lesson. The lab also emphasized kinesthetic experiences with forces, both as the applier and receiver of the force (for descriptions of kinesthetic intuition in expert problem solving, see Clement, in press). In addition, the second version used discussions on an increased number of other concrete examples such as the inertial balance and examples of inertia from daily life.

d. *Intermediate concepts as stepping stones*

Examples of "holdback" and "keeps going" tendencies of large masses were identified and labeled. Students were observed to begin using these terms very quickly in discussions after their introduction by the teacher. (Later they were integrated into the single concept "inertia" as resistance to positive or negative acceleration.) This represented a strategy of using more approachable

"intermediate concepts" which are stepping stones to the physicist's more abstract and general concepts. These terms allow both teacher and student to talk about specific alternative conceptions such as "not mentally separating the holdback tendency of mass from frictional forces".

It is interesting to note that there is evidence that Newton employed similar intermediate conceptions. The quotation below is from one of the last manuscripts drafted by Newton prior to writing the Principia. If we make a correspondence between "holdback" and Newton's "Resistance" and between "Keeps going" and Newton's "Impetus", we see that he was struggling with a very similar distinction between natural subdomains. Up to this point in this writings he has spoken separately about these two tendencies related to inertia, but at this point he begins to talk about them as two sides of the same coin, and gives a relative motion argument for their equivalence. It is tempting to think of this passage as a key point in the invention of the concept of inertial mass. This conceptual integration was one of the last (and by implication one of the most difficult) hurdles that Newton had to overcome before writing the Principia. (We have shied away from relying on the relative motion argument for students, because of its somewhat counterintuitive and abstract nature.)

> The internal force of matter is the power of resistance by means of which any one body continues so far as it can in its state of rest or moving uniformly in a straight line: and it is proportional to its body nor differs at all from the inertia of matter except in our mode of conceiving it. In fact a body only invokes this force in changes of state produced in it by another force impressed on it, and its exercise is *Resistance* [holdback] and *Impetus* [keeps going] which are distinct only in relation to each other ... It is customary to attribute resistance to bodies at rest and impetus to those in motion: but motion and rest as commonly conceived are distinct only in relation to each other: nor do those things truly rest which are regarded as if they rested by ordinary people. (Isaac Newton, as quoted in Herival, 1965, p. 318)

e. *Selected examples to encourage new concept differentiations*

The conceptual difficulties listed in Table 1 are for the most part differentiation difficulties. These are somewhat different than difficulties involving an alternative conception in the form of a model competing with the physicist's model (such as the belief that an object moving in a curve will continue to do so in absence of external forces.) In the skateboard lab and elsewhere, separate discussion questions and follow up activities were designed to address the concept differentiation issues in Table 1 above; many of these were glossed over in the first version because we did not have as clear an image of the different difficulties. Version one moved too quickly to the physicist's abstract form of the relationship between inertial mass and acceleration. Even though version one avoided quantitative abstractions it was still *too abstract at the qualitative level.*

For example, in version two, discussion of the PSSC inertial balance with a wire added to support the weight (will the balance vibrate faster with or without a supporting wire for the weight?) was designed to address the confusion between the holdback property and gravity as the source of smaller acceleration in horizontal motion. The inertial balance also seemed to give the students an opportunity to apply what they had learned in the skateboard lab to a somewhat more (but not too much more) complicated case. Students rated the inertial balance discussions highly, and there was a surprisingly long discussion in one of the standard level classes about it. Thus, version two used specific activities designed to motivate new concept differentiations in discussion.

Specific Changes in the Gravity Lesson Making it More Conceptually Focused

Although the inertia unit was more substantially reworked in terms of conceptual focusing, there were several changes to the gravity unit which fall under this category.

a. Subdomains identified

Subdomains were identified which physicists consider similar but which students may not, and examples of each were included. For example, four subdomains of gravity were identified; gravity between celestial objects, falling objects on earth, stationary objects on earth, and gravity between everyday objects. The first year's lessons dealt with only two of the four (gravity between celestial objects and gravity between ordinary objects). We realized that the revised lessons needed to deal with all four, and specific activities were designed to address difficulties in each domain.

b. More familiar situations were used as starting points in the lesson

More target or focusing questions were added, and the sequence of these questions was changed to move from the concrete and familiar (gravity on earth) to the less concrete and less familiar (gravity between small objects and in space). One of the first questions in the first version of the lessons dealt with the equality of forces between the earth and the moon. By contrast, the new lesson initially shied away from the less familiar domain of space by focusing on different student ideas about the cause for gravity on earth (e.g., air pressure and the earth's rotation).

Summary

The first major cluster of hypotheses explaining the performance gains has been termed "conceptual focusing". Our increased comprehension of details in the map of students' conceptual difficulties led to a number of changes to the lessons that appeared to improve their conceptual focus so that they could more accurately address those difficulties. These were: recognition of natural subdomains of events for naive students that are different from the physicist's domains, where we needed to create specific examples; increased use of concrete examples and laboratories; using "intermediate concepts"; and an increased focus on concept differentiation. Our new image of the students' entry concepts recognized that these concepts were more tied to everyday events at a lower level of generality than the physicist's concepts, and as a result we made the starting points for these lessons more specific and concrete.

Splitting Units to Allow for Revisiting

Both the gravity and inertia units were lengthened and split into two sections separated in time to allow more extended treatment of individual conceptual difficulties and for revisiting (Arons, 1981), of the new conceptions. Especially for difficult concepts, it may be important to spread learning out over a longer period of time. This makes sense motivationally, in order to avoid spending more than a few lessons at time on a single difficult topic. It also makes sense cognitively, in order to have students learn a new concept via several different learning pathways. This makes it more likely that the resulting knowledge will be accessible in a broader range of contexts later.

More Emphasis on Oral and Written Explanations

In the second version, we increased the number of occasions where we required students to give oral and written explanations. This was motivated by observations of uneven participation in some class discussions, and concerns about the importance of having each student be actively thinking about the new concepts. We implemented this in several ways:

1. The skateboard laboratory involved every student in making written predictions, observations, and explanations. Thus, it provoked more extensive cognitive interactions on basic issues than did the corresponding demonstration in the first version of the lesson. The students' written explanations explicitly articulated a number of alternative conceptions that were used in

large group discussions in the following class. Students rated the lab as helpful and the discussions of it were observed to be long and energetic.

2. Students were assigned homework questions which focused on specific conceptual issues and asked for written qualitative explanations.
3. We observed that the initial quality of such written explanations was far from ideal. An emphasis on generating explanations needs to be accompanied by some mechanism for encouraging students to *criticize* and *refine* these explanations (for a description of these processes in a case study of expert explanation strategies, see Clement, 1989). There are several subgoals here, the first two of which are metacognitive goals. Students need to:
   (a) Develop a habit of evaluating their conceptions critically, especially with regard to whether they "make sense".
   (b) Improve the general level of care and precision in their use of concepts, distinctions, and terminology.
   (c) Compare their explanations, including those that contain alternative conceptions, with various explanations and with conflicting observations.

In a teaching strategy using "explanations criticism sheets", students were given a list of possible explanations to criticize. For example, one sheet considers the question, "What is the main reason that a more massive skateboarder is harder to stop?" Students were asked to criticize different explanations answering this question, such as "more mass means more friction". Several of the explanations included common alternative conceptions, and one explanation was the physicist's explanation.

Students are rarely asked to criticize anything in science classes! This strategy was designed to encourage such processes. It represents a compromise between an unstructured discovery learning approach where students would need to tackle the daunting task of constructing the Newtonian explanation of inertial mass, and the didactic strategy of simply presenting them with the Newtonian model. These sheets were successful in drawing out a number of key issues in large group discussions in the advanced class. Perhaps the most important effect of this strategy is that it gets the students talking about "why" questions and the qualitative conceptual physics models which provide explanations for everyday phenomena.

Remaining Difficulties with the Lessons

Complex Explanations are Difficult in Lower Level Classes

Observations of large group discussions of the diagram explanation sheets in the standard classes indicated some confusing exchanges between the students, partly because there are a number of elements to talk about at once in the explanations, and the students sometimes lack sufficient vocabulary to say what they are thinking without being able to point to elements in the diagram. This suggests using more elaborate labels on the diagrams, but also suggests that they be used with small groups or pairs (where pointing is more possible) to improve the communication process in the future.

Students' Reactions to Partial Models

The gravity lesson introduced several partial analogies for gravity such as springs, magnets, etc., and these were critiqued in discussion. The analogies for gravity did not seem to be used by students in later explanations. A hypothesis about why the analogies were not used in student explanations is that they are not plausible *explanatory* models of gravitational interactions (i.e., the mechanism proposed for the force is not perceived by the students as "actually operating in the situation" - see Brown and Clement, 1989 for further discussion of explanatory models). For most students, a spring analogy (e.g., from a man to the center of the earth) is not an explanatory analogy. It is unclear whether such an analogy would be helpful to a student who is looking for a causal explanation of gravity (versus comparison to a system which behaves like gravity in some ways). By contrast, for example, a model of a table as springy (versus just a rigid barrier) often does become explanatory for students and increases the plausibility of an upward force from the table when a book is resting on it (Brown, 1987, in press).

Another interesting observation came from students' interactions with the "masslet model". In this model, objects are conceived as composed of small, standard bits of matter (masslets). Each masslet in an object then pulls on every other masslet in another object, and the force between the objects is the sum of the forces between each pair of masslets in the objects (a Cartesian product leading of the relation $F = M \times m$). Although most students seemed eventually able to use this model effectively, we were surprised by the number of students who initially had difficulty with this model.

One explanation for this is that the model is based on a view of forces arising from interactions, whereas many students view force as a property of objects. Under the latter view, a masslet pulling on numerous other masslets would "use up" more force and get "tired" faster than a masslet pulling on only a few masslets. Such arguments came up frequently in class discussions. Thus, masslets on the moon would tire faster than masslets on the earth since each moon masslet has to pull on more earth masslets than vice versa. This impresses on us once again the often pervasive and persistent nature of alternative conceptions affecting students' comprehension of instruction.

Discussion

General Principles

We can now summarize some grounded hypotheses which may impact on the development of other lessons.

1) The Importance of a Detailed Map of the "Conceptual Territory"

Many improvements resulted from a finer comprehension and articulation (on the part of the lesson designers and teachers) of: (a) the student's entry concepts: alternative conceptions, initial subdomains of experience used, and elusive conceptional distinctions; and (b) the consequent image (by contrast) of the expert's conceptual map showing assumptions and tacit knowledge one usually takes for granted in the domain.

2) Improved Conceptual Focus

Improved mapping of preconceptions and target conceptions can lead to the design of more appropriate activities, examples, and structuring in the lesson, in the following ways:

a) Newly recognized subdomains where separate examples need to be discussed because students do not reliably generalize across these subdomains; and putting these in order of difficulty.
b) Increased use of concrete examples, including qualitative laboratories.
c) Selecting examples for specific concept differentiations.
d) The use of intermediate concepts (such as "keeps going tendency") versus immediate use of fully general, but more abstract, concepts.

3) Splitting Units to Allow for Revisiting

By breaking the unit into parts separated by several weeks, students had the opportunity to "revisit" the concept in a new context.

4) Increasing Verbal Explanation

The second version of the lessons required much more articulation, criticism, and refinement of qualitative explanations.

5) Students' Difficulties with Certain Models

The students' difficulties with some of the models and analogies used (especially in the gravity unit) were somewhat surprising and lead us to hypothesize that students can fail to apply models which simply provide an example of a system which *behaves like* the phenomena in some way and do not provide a causal mechanism for the phenomenon. We were also surprised at the students' difficulties with the masslet model, which may have been uncompelling due to a conflicting preconception of force. This impresses us once again with the often persistent and pervasive nature of alternative conceptions affecting students' comprehension of mechanics.

Implications for Further Research

In a curriculum development effort of this type, many changes to the lessons are made in each cycle of testing. Thus, our inferences about individual causes of improved learning must remain as grounded hypotheses rather than firm conclusions. Further research might take the form of testing two lessons with only one major difference between them, but there are many such differences to be tested. An alternative is to collect real time data on students' actions and statements during learning which indicate directly the importance or folly of a certain instructional technique. Such data is available to a limited extent in tapes of classroom discussions, and to a greater extent in learning process studies of individuals or small groups "learning aloud". Such studies are very much needed to provide evaluations on the effectiveness of the instructional strategies suggested in this paper.

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Appendix: Descriptions of the Lessons

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Gravity Unit Description

The gravity lessons consisted of two segments - Gravity I and Gravity II. Following is a brief description of the lesson sections in each segment.

Gravity I

To begin, the teacher draws a picture of a person in Australia and asks students how the gravity in Australia compares to the gravity in the United States. This leads to a discussion of the general questions: "What exactly is gravity?" and "What causes gravity?" Two common causes given are air pressure and the rotation of the earth.

To address the air pressure conception, the teacher asks students to predict the reading on a spring scale in an evacuated bell jar. Once students grapple with their ideas for some time the teacher performs the demonstration, and then asks what causes gravity if not air pressure. To address the rotation conception, the teacher asks students to predict the reading on a spring scale if the earth spins faster on its axis. The teacher draws out analogies by having students think about what happens on a rotor or on a merry-go-round at an amusement park and then demonstrates the situation by spinning and holding a spring scale and mass at arm's length. This shows that the earth's rotation would cause a slightly lower reading on a scale and thus could not be the cause for gravity. At this point NASA video clips are presented with the objective of helping students imagine what a zero gravity situation would be like.

To get at the idea of gravity between ordinary objects, students are asked whether there is a force of gravity between two tennis balls. The same question is then asked about two stars and about the Earth and Mars. To give students some experience with gravity between ordinary objects, the PSSC film "Forces" is shown (the Cavendish experiment with water bottles and sand bags).

In an attempt to create a mental model that describes gravity, the teacher asks students to think of situations such as two blocks connected by a spring, or a magnet pulling on paper clips. Similarities and differences of all the models are discussed, with an emphasis on gravity compared to magnetism. Students working in pairs are asked to describe an analogy helpful in explaining gravity between two planets and to list the weaknesses of the analogy.

Gravity II

This lesson concentrates on the idea of gravity as an interaction. To begin, students are asked to compare the gravitational force of a large truck on a small water bottle and the small water bottle on a large truck. The idea of "masslets" (small standard piece of matter) is reviewed as a helpful way of thinking about properties of matter. It is suggested that although the standard is arbitrary, a gram is a good candidate for this standard piece of matter.

Students develop and critique mental models that help visualize the gravitational forces acting between masses. Some models are strings, rubber bands, and springs. The teacher points out that science has not agreed upon, easily visualized, models of gravitational forces.

Then two small objects are considered. One has two masslets and the other has three masslets. The teacher draws lines that indicate the gravitational pull between masslets and then asks "Which exerts a larger gravity force?" At this time the teacher affirms the equality of forces between objects with different number of masslets since the number of lines going to and from each object is equal. Students are asked about a man standing on the Earth and whether the man exerts any upward gravitational force on the planet Earth. If not suggested by students, the teacher introduces the idea of combining the lines of force of the man and the Earth into one spring going from the man to the center of the Earth.

The class is presented with a situation in which object A has three masslets and object B four masslets. Students are asked whether the force of A on B will change if a masslet is removed from B. They are then challenged by the teacher to explain why it is wrong to suggest that A is still just as strong since it still has the same number of masslets.

Inertia Unit Description

The inertia lessons are comprised of two segments - Inertia I and Inertia II. Following is a brief description of the final version of the lesson.

Inertia I

Students engage a skateboard laboratory, in which students accelerated and decelerated other students on skateboards. The teacher introduced the intermediate terms "hold back tendency" and "keeps going tendency" when talking about the lab and about examples of everyday manifestations of inertia such as seat belts and shoveling snow. Students then selected a choice that made the most sense from several written and diagrammed explanations reflecting various alternative conceptions as well as the physicist's view. This homework was discussed very thouroughly by analyzing each possible argument in large group discussion. The idea of masslets is revisited as small bits of matter which resist being started (hold back) or stopped (keeps going). At this point, an inertial balance demonstration shows that the balance moves an equal distance on each side, indicating the same amount of "hold back" and "keeps going". Then the balance is demonstrated with added mass. Students are asked

to predict what will happen. They are also asked if the "hold down" tendency is important in the inertial balance. In order to cancel out the effect of the "hold down" tendency a wire is attached to the ceiling in order to hold the mass. This leads to the conclusion that the "hold down" tendendy is not important in the inertial balance. During classroom discussion it is agreed that "hold back" tendency and "keeps going" tendency are equal. The term to be used for both tendencies is inertia. A free body diagram of a skateboarder is discussed by analyzing the forces acting on it and by predicting what will happen.

Inertia II

NASA films that introduce weightless environments are presented. Then students are asked about astronauts pulling objects of different mass in space - which would require more force to accelerate it? As a potential anchor, students are then asked which has a better chance of waking you up in space, a 16 kg watermelon floating through the air and colliding with you at 5 mph, or a 1 g whiffle ball colliding with you at 5 mph. Other questions are asked about keeps going and holdback in space. The teacher then asks whether a heavy object or a light object will fall at a faster rate and performs the demonstration. It is also established that the larger object has a greater force acting on it. Students are reminded that weight measures the force of the earth pulling on an object. Thus, a paradox is established: the smaller object falls just as quickly as the larger object, yet the forces on the objects are unequal. To explore this paradox, students are asked whether the earth pulls more on a Cadillac than on a motorcycle, and whether the Cadillac is harder to pull. The diagram accompanying this question shows the Cadillac and motorcycle on a high platform jutting sideways out from a spherical earth. After some discussion students are asked whether this is analogous to the previous problem of the astronaut needing to exert a larger force to pull a larger object. It is confirmed that it is harder for the Earth to accelerate the Cadillac toward it, but that compensating this is the fact that the gravitational force an the Cadillac is larger. Symbolically, $F/M = 10$, $f/m = 10$.