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AUTHOR	Clement, John
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ABSTRACT

Reviewed are findings on misconceptions in mechanics and their instructional implications. Many misconceptions are widespread and resistant to change but students have useful intuitions and reasoning processes that could be used more fully. One strategy for dealing with misconceptions is described. It stresses anchoring intuitions, analogical reasoning, thought experiments, and classroom discussion. Data showing significant gains in experimental classes using this strategy. (Author/RH)

THE USE OF ANALCGIES AND ANCHORING INTUITIONS
TO REMEDIATE MISCONCEPTIONS IN MECHANICS

John Clement
Department of Physics and Astronomy
University of Massachusetts/Amherst

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ABSTRACT

Findings on misconceptions in mechanics and their instructional implications are reviewed. These indicate that many misconceptions are widespread and resistant to change, but that students also have useful intuitions and reasoning processes that could be utilized much more fully. One strategy for dealing with misconceptions based on the use of anchoring intuitions, analogical reasoning, thought experiments, and classroom discussion is described. Data showing significant pre-post differences in favor of experimental classes using this strategy is reported.

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THE USE OF ANALOGIES AND ANCHORING INTUITIONS TO REMEDIATE MISCONCEPTIONS IN MECHANICS

In the first half of this paper I review findings on misconceptions in mechanics and their instructional implications. This is not intended to be a complete review but does indicate representative sources of evidence for the findings. In the later sections I focus on our own attempts to design instructional strategies for dealing with misconceptions. Although long-term process goals such as the development of general problem solving and inquiry skills are certainly as important, if not more important than content goals, in this paper I will restrict discussion to the goal of finding the best way to develop conceptual understanding in students that supports skilled problem solving in physics.

Based on prior experience in tutoring sessions and interviews with physics students, Clement (1978) developed a model of types of knowledge structures used in physics: Practical knowledge, qualitative physical models, mathematical models, and equations. Clement was influenced by Easley's (1978) model of types of knowledge to be studied in (and developed in) science students. Easley was in turn responding to a description of levels of knowledge in science by Hempel (1970).

Larkin (1983) hypothesized that students need to develop knowledge at three different levels: naive, physical, and mathematical representations. She believes that these multiple levels of knowledge enable experts, unlike most novices, to work forward during a problem solution, gradually generating and elaborating a qualitative knowledge representation for the problem situation. This paper concentrates on the problem of helping students

overcome persistent misconceptions occurring at the first two levels in mechanics. It also focuses on a relatively coarse-grained level of theoretical description which I hope will be useful for communicating with teachers.

SUMMARY OF ARGUMENTS

In this section the main arguments in the paper are summarized. These are then discussed in greater detail in later sections. Since my research is strongly driven by what I believe are critical instructional issues, I have found that it makes most sense to present together applications-motivated research questions, research findings, and implications of the findings for teaching.

I. The Problem

1. Misconceptions are Widespread

Question 1. How can we characterize the general level of understanding students attain in a traditional physics course?

Finding 1. While taking physics many students can be described as "formula centered" both in their knowledge of physics and in their approach to problem solving. They are able to solve some problems that require only plugging numbers into formulas and manipulating those formulas, but are still unable to solve some very basic qualitative problems. Certain patterns of common qualitative errors across students and problems indicate that many students possess a variety of common misconceptions which can produce repeated errors.

Instructional Implication 1. Courses need to place increased emphasis on conceptual understanding at a qualitative level.

2. Many Misconceptions are Preconceptions

Question 2. What are the origins of such misconceptions?

Finding 2. Pretests and interviews before courses indicate that many misconceptions are preconceptions students bring to class with them. Apparently one cannot consider the student's mind to be a "blank slate" in this area.

Implication 2. Many errors that teachers ascribe to poor reasoning may in fact be due to preconceptions. Teachers need to take preconceptions into account during instruction.

3. Many Preconceptions are Persistent

Question 3. Are preconceptions that produce errors amenable to a quick-fix approach? Can we use straightforward, traditional teaching techniques, or do we need non-traditional techniques?

Finding 3. Many preconceptions are deep seated and resistant to change. This is now supported by a number of different types of evidence: errors on post-course tests, resistance to tutoring, expressions of conviction in interviews, and historical precedents.

Implication 3. The fact that some preconceptions resist change in the face of traditional lecture-demonstration based teaching means that more powerful teaching techniques will have to be devised. Apparently the direct transmission model of direct verbal input from lectures or texts to students who are "empty vessels" is not adequate in these cases.

II. One Approach to Dealing with Misconceptions

4. Students Have Inconsistent Beliefs

Question 4. What is the nature of misconceptions as knowledge structures? How general are they?

Finding 4. From the physicist's point of view, students' conceptions are inconsistently applied depending on the context. For example in the area of Newton's third law, students will exhibit correct behavior on some cases but incorrect behavior on others in what to the physicist look like very similar problems. This can be explained by assuming that both "correct" and "incorrect" conceptions can occur at a low level of abstraction and generality -- not as specific as individual episodic memories of events, but not as general as physics principles.

Implication 4. Misconceptions can be used to advantage in the classroom. From their persistence and low level of generality we infer that existing knowledge structures need to be engaged through discussion of a large number of examples so that the student can play an active role in questioning and modifying them. The natural conflict between "correct" and "incorrect" conceptions can be used to create controversy and cognitive dissonance that promotes learning.

5. Students Have Anchoring Intuitions

Question 5. Is there a positive side to students' conceptions? Are there particular key examples or qualitative problem situations which are especially important to introduce and discuss in courses?

Finding 5 . In addition to misconceptions, diagnostic tests and interviews show that students enter courses with useful ideas we call anchoring intuitions which are in rough agreement with accepted theory.

Implication 5. Anchors can be used as starting points for instruction as a way of making physics make sense at an intuitive level. Students should attain a greater understanding of physics ideas if they are grounded in prior intuitions whenever possible.

6. Experts and Students Have Intuitive Reasoning Processes Which Can be Utilized in Overcoming Conceptual Difficulties

Question 6. What reasoning processes are important at the level of learning qualitative physics from key examples?

Finding 6. Reasoning by analogy is one powerful form of intuitive reasoning in experts and students. Experts use special techniques such as "bridging" to establish the validity of an analogy. Anchors and bridges can be used together to help students overcome misconceptions as indicated by pre and post tests with experimental and control groups.

Implication 6. Analogical reasoning and "bridging" can be used to extend useful intuitive knowledge from anchors to areas where misconceptions occur.

DISCUSSION

I. The Problem

1. Misconceptions Are Widespread

Findings. Surveys of work on students' preconceptions and misconceptions in science have been provided by Driver and Easley (1978), Helm and Novak (1983), and Fisher and Lipson (1983).

There is evidence that many students taking calculus-based physics harbor misconceptions at a basic qualitative level even though they may be proficient at the use of physics formulae (Clement, 1981b). These misconceptions have been documented in several areas of mechanics, including Newton's first and second laws (Clement, 1982a) (diSessa, 1982), and torque (Barowy and Lochhead, 1981). McDermott (1984) reviews other work on misconceptions in mechanics, including studies by Viennot (1979), Champagne,

et al, (1980), Trowbridge and McDermott (1981), McCloskey et al (1980), Gunstone and White (1981), Erickson and Aguirre (1984), and Whitaker (1983), among others. See especially Hestenes (1985). These findings indicate that courses need to place increased emphasis on conceptual understanding.

2. Many Misconceptions are Preconceptions

Many misconceptions are not "miscomprehensions" of presented material but are preconceptions that students bring to class with them. We found such preconceptions in our work on torque and Newton's first and second laws cited above. Preconceptions producing consistent error patterns have been identified in the areas of static forces exerted by objects (Minstrell, 1982), centrifugal force (Viennot, 1979), velocity (Trowbridge and McDermott, 1980), elastic forces, Newton's third law (Maloney, 1984), and curvilinear motion (McCloskey et al, 1980), among others.

Implications. When students with these beliefs produce incorrect answers in the classroom, the instructor may in some cases assume that the cause is "low intelligence" or poorly developed reasoning skills, when in fact the cause is the student's alternative knowledge structures. It is important for teachers to become sensitive to such distinctions because the indicated teaching strategies are quite different in each case. Avoiding this confusion might have an impact on the way teachers view students and in turn, on the way students view themselves.

3. Many Preconceptions are Persistent

It is clear that some preconceptions are more deep seated than others. As Chaiklin & Roth (1986) point out, incorrect answers to diagnostic problems may not always reflect deeply held preconceptions since students are willing

to use beliefs they are uncertain about in problem solving. But there are several different types of evidence indicating that some preconceptions are very deepseated, including: post course tests, resistance during tutoring, expressions of conviction in interviews, and historical precedents.

Post course tests. In many of the studies above, including Clement (1982a), Viennot (1979), Hestenes (1985), and Maloney (1984), the preconceptions were still present in many students after a course in physics. Thus, traditional teaching practices do not address the problem sufficiently. Other researchers who have documented persistence are Sjoberg and Lie (1981), Driver (1973), Peters (1982), and Caramazza et al (1981).

Tutoring. Another indication of the deepseatedness of some preconceptions comes from real-time data on learning. Nowhere is this more striking than in individual tutoring sessions where a carefully constructed, animated explanation delivered by the tutor is completely rejected or misassimilated by the student. This is discouraging for both teacher and student. Unpublished work from tutoring interviews and classroom discussions (Clement & Brown, 1984) shows students expressing disbelief concerning many aspects of standard physical theories in mechanics and reveals students actively producing counter arguments and other indicators of resistance to change. Lochhead (1981) found that college engineering students performed very poorly on explanation questions immediately after lecturing explicitly about common preconceptions surrounding F = ma.

Conviction. Students will express their conviction to a teacher or interviewer directly in various ways. They may show incredulity at the physicist's point of view. We are currently collecting data on confidence scale ratings in order to determine the level of certainty students attach to various preconceptions.

Historical Precedents. Some preconceptions in mechanics bear certain similarities to beliefs held by pre-Newtonian theorists. There are some similarities between statements made by college students and a discussion of impetus in projectiles by Galileo (Clement, 1982a). In the case of some of the transcripts, it is remarkable how similar the statements are, given that the speakers are in different cultures and separated by over 300 years. Historical parallels have also been discussed by Wiser and Carey (1983). These precedents support the idea that some preconceptions have common intuitive roots derived from everyday experience.

Why certain preconceptions are deepseated is an important theoretical problem. One possible explanation is that they are encoded in a perceptual/kinesthetic form (Clement, 1983a) that is quite unlike a memorized rule or a passive set of verbal propositions which would presumably be easy to "delete". Some case studies (Clement, 1979) indicate that they have become "embedded into the system" at a perceptual-motor ("gut") level rather than at an abstract level.

Another possibility is that some preconceptions form partially coherent systems that can support each other (Clement, 1983). That there are multiple misconceptions which interfere with the attempt to teach a coherent system of Newtonian ideas is now well established. What remains to be investigated empirically is the question of whether different preconceptions at a low level of generality can be somewhat coherent themselves in the sense of supporting each other.

Implications. The resistance of preconceptions to change indicates that traditional instruction will not work where deep seated preconceptions are concerned, and that significantly new teaching methods need to be developed.

One Approach to Dealing with Misconceptions

4. Students Have Inconsistent Beliefs.

The fact that subjects can hold multiple views of the same concept or example has been discussed by Chaiklin & Roth (1986), Easley (1981), Clement (1982c), and Viennot (1979). Clement (1982a) reported that students draw in a force in the direction of motion on the upswing of a pendulum more often than on the downswing. As exemplified in the hand on spring vs. book on table cases discussed below, the student can also simultaneously harbor in memory an anchor and a misconception that are diametrically opposed. This is partly due to the fact that the student's knowledge schemas are packaged in much smaller pieces than the physicists' knowledge, and because each schema is activated only in certain contexts (diSessa, 1985).

Implications for instruction. The tension produced by such oppositions can be used to advantage in instruction. Two types of tension can be used: The tension between a misconception and a correct conception in the same student; and the tension between students who hold the correct point of view early on and students who do not. In the first type, one attempts to draw out both correct and incorrect conceptions which are activated in slightly different contexts in the same student and play them off against each other. In the second, one encourages controversy centering on opposite views held by different students. These tensions have the potential to create some unusually exciting and motivating discussions in the classroom that should act to increase student involvement and retention. A description of a teaching technique utilizing these tensions is given in the next two sections.

5. Students Have Anchoring Intuitions

Given the persistence of many preconceptions, we can hypothesize that it is only by tapping existing thinking processes in students and getting them to actively manipulate existing conceptual material that they will make progress. Therefore I believe it is extremely important to also identify positive aspects of naive student thinking, aspects which can be tapped and put to good use in instruction.

For example, in a survey of 112 high school chemistry and biology students who had not taken physics, we found that 76% of the students believed that a table does not push up on a book. Tutoring interviews and class discussions indicate that many students express disbelief in the physicist's view and have a deeply held belief that stationary objects are rigid barriers which cannot exert a force on their own other than their "weight" (sic). On the other hand, 96% of the students did believe that a spring pushes up when it is compressed with one's hand (Clement, 1986). The contrast between these results is interesting since the physicist views these two situations as essentially identical. diSessa (1983) refers to the concept of springiness as a "phenomenological primitive" and discusses the evolution of the individual's intuitions that is needed to become skilled in physics.

The hand on the spring situation is a useful starting point for instruction since it draws out a correct intuition from students. For this reason we call it an "anchoring situation" that draws out an "anchoring intuition". An anchoring intuition is a largely self-constructed belief held by a student which is roughly compatible with accepted physical theory. Such a belief may be articulated or tacit. The notion of searching for anchoring intuitions opens up a large field for needed research that should complement the ongoing research on misconceptions. Potential anchoring examples can be listed by skilled teachers, but they require empirical confirmation. For

example, we hypothesized that hitting a wall with one's fist might be an excellent anchoring example for the idea that a static object can exert a force. Surprisingly however, only 41% of pre-physics students tested agreed that the wall would exert a force on one's hand. Empirical studies can determine which situations will appeal the most to students' intuitions. Thus one must find the "right" analogous case to use as an anchor -- not just any concrete example that makes sense to the teacher will work.

6. Experts and Students Have Intuitive Reasoning Processes which can be Utilized in Overcoming Conceptual Difficulties

Analogical reasoning. Studies of analogical reasoning patterns in experts and novices suggest some new methods for using analogies and examples to create dissonance and subsequent reorganization during instruction. The spontaneous use of analogies has been documented in thinking aloud interviews with scientists (Clement, 1981), and with students (Clement, 1978a, 1987). Given that the goal of developing more general knowledge structures from intuitions that exist at a low level of generality, focusing on analogies between examples should help to integrate structures into larger, more general units.

Using analogies in instruction. Minstrell (1982) has reported some success in using key examples in Socratic teaching for the book on the table problem. In what follows we will build on his ideas by emphasizing the role of chains of analogies and mechanistic models in such lessons.

Unfortunately we have found that when an anchoring intuition is drawn out in students, this is not enough to insure its successful application. The physicist can apply an idea such as springiness to a wide domain of examples (e.g., any solid object). Unfortunately students often do not believe that an anchoring example such as the hand pushing a spring is analogous to the book

on the table or to other examples in this domain. Experts have been observed to use special patterns of analogical reasoning such as "bridging" in order to stretch the domain of a key analogue example and overcome a conceptual difficulty (Clemen .), and we suspect that these patterns are useful for overcoming conceptual difficulties in students as well. The reasoning pattern of "bridging" is described in the example below.

The bridging strategy. In almost all cases students believe in the anchoring example that a spring can push back on one's hand, but many are still unconvinced that there is a valid analogy relation to the case of the book on the table. A useful strategy is to attempt to find an intermediate third case between the original case and the analogous case. This is termed a bridging analogy. Figure 1 shows a flexible board case used to help convince students that the analogy between the "hand on the spring" anchor and the targeted "book on the table" case is valid. Here, the idea of a book resting on a flexible board (case B) shares some features of the book on the table (case C) and some features of the hand on the spring (case A). The subject may then be convinced that A is analogous to B and that B is analogous to C with respect to the same important features, and thereby be convinced that A is analogous to C. Such bridges are not deductive arguments, but experts have been observed to use them as a powerful intuitive argument. Presumably, this method works because it is easier to comprehend a "close" analogy than a "distant" one. The bridge divides the analogy into two smaller steps which are easier to comprehend than one large step.

Lessons can also use several intermediate bridging cases, as shown in the outline of the lesson on static forces shown in Figure 2. Visualizable models and empirical demonstrations are also used where appropriate. The

teacher asks the class to discuss their opinions on each of the thought experiment examples without telling them the answers.

First the target problem is introduced: the question of whether the table pushes up on a book. Then the hand on the spring case is discussed and agreed upon as an anchor. The foam and flexible board cases are then introduced into the discussion. The flexible board case usually promotes the greatest discussion, and a number of students switch to the correct view at this point. The teacher then introduces a microscopic model of rigid objects as being made up of molecules connected by spring-like bonds. Finally the students view a demonstration where a light beam reflecting off of a desk onto the wall is deflected downward when the teacher stands on the desk.

Thus the lessons use a sequence of analogous cases to connect an anchoring example to the target problem, and also to develop a visualizable model of the mechanism(s) providing forces in the target problem. Demonstrations are used either to disequilibrate students preconceptions or to support a key aspect of the analogue model such as the presence of deformation in rigid objects.

Results from teaching experiments. We have attempted to use this strategy in tutoring studies and class sessions with high school students. Qualitative observations from video tapes of these classes indicate that: 1) students readily understand the anchoring case; 2) many students indeed do not initially believe that the anchor and the target cases are analogous; 3) the bridging cases sparked an unusual amount of argument and constructive thinking in class discussions; 4) the lessons led many students to change their minds about beliefs such as: "A table cannot exert an upward force on a book at rest on it"; and 5) students were observed generating several types of interesting arguments such as generation of analogies and extreme cases, explanations via

a microscopic model, arguments by contradiction from lack of a causal effect, and even spontaneous generation of bridging analogies (Steinberg, 1986).

Experimental vs. control classes. We also tested the effectiveness of the strategy described above by designing other experimental lessons using the strategy and giving identical pre and post tests to experimental and control classes. Altogether, five experimental lessons were designed in three areas: static forces as described above, frictional forces, and Newton's third law for moving objects. Members of the design team were myself, James Minstrell, Charles Camp, David Brown, Melvin Steinberg and Klaus Schultz. Each lesson was based on the use of analogies to develop connections to an anchoring physical intuition and to develop a visualizable model of the target situation. Control classes were normal first year courses in physics.

The test consisted of 16 questions on common misconceptions and included both near and far transfer questions. The pre and post tests were given about 6 months apart: in the second month of the course just before the first experimental lesson and again two months after the final experimental lesson.

Results are highlighted in the right hand column of Table 1. The experimental group achieved significantly larger pre-post test gains than the control group, both overall, as shown in Table 1, and in each of the three areas, as shown in Table 3. The difference between the overall gains was larger than two standard deviations. We interpret these results with some caution, since the tests were multiple choice tests, and more accurate assessment of students' understanding requires clinical methods. Also, matching of experimental and control groups was limited by characteristics of the available classes. The school where the experimental classes were conducted and one of the control schools had upper level classes of first year

physics as well as lower level classes, while the second control school grouped students homogeneously.

However, as shown in Table 2, even when the lower level experimental classes (with a teacher who was relatively new to physics teaching) are compared with the homogeneous control classes (with an experienced person considered to be a master physics teacher), there are large significant differences in favor of the experimental group.

DISCUSSION

The experimental teaching method described first attempts to ground the student's understanding on a physical intuition about a familiar case. An important implication for curriculum development related research is the need to search for such anchoring intuitions. In areas where students have insufficiently developed anchoring intuitions they may need to be developed by real or simulated experiences such as Arons' activity of having students push large objects in a low friction environment, McDermott's (1984) use of air hoses to accelerate dry ice pucks, or diSessa, Horwitz, and White's use of dynaturtle (White, 1984).

The teaching strategy then attempts to build on and extend the anchoring intuition by using analogical reasoning. In the case of common misconceptions the problem is that students will often not be able to understand how the target case can possibly be analogous to the familiar anchoring case. Presenting the right analogy is not enough -- the student must also come to believe in the validity of the analogy. This can take more time and energy than is usually recognized. The technique of bridging by using chains of analogies combined with discussion to encourage active thinking appears to be helpful for this purpose.

The anchor also serves as the metaphorical basis for a visualizable model such as the idea of molecules with spring like bonds between them. Such models are not simply a set of common features abstracted from observed phenomena (we cannot observe atoms or springs inside of tables). Like other models in science they are imaginative constructions which have metaphorical content.

Such an approach attempts to depart significantly from a model of teaching where knowledge is "piped" directly from teacher to the empty vessel of the student. It does so by drawing out and developing existing prior knowledge in the subject. The teaching approach attempts to interact with this knowledge rather than to transfer knowledge. It interacts with prior knowledge of two types: anchoring intuitions that are in agreement with accepted theory and misconceptions that are not.

However, it takes a research effort to develop and optimize this type of approach. Maps of students' misconceptions and anchoring intuitions are needed. Knowledge of students' intutitve reasoning skills is also needed. The present study provides some encouragement regarding the possible payoffs of such an effort .

APPENDIX I:

A Bridge Used by Newton

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

The proposed analogy relation is represented by the dotted line in Figure 3. Essentially this conjecture says that the same causal mechanism is involved in making the moon revolve around the earth and making an apple fall. A multiple bridge used by Newton to support this analogy in his Principia is shown in Figure 3c. This is the idea of a cannonball fired faster and faster until it enters into orbit around the earth -- a premonition of modern rocketry.

These bridging cases stand between the case of a cannonball dropped straight down and the case of the moon circulating in orbit. They help one see how the motion of a dropped object and the motion of the moon can have the same cause in the gravitational pull of the earth. Thus bridging cases are to be found in the history of science as well as in the protocols of expert problem solvers (Clement, 1986).

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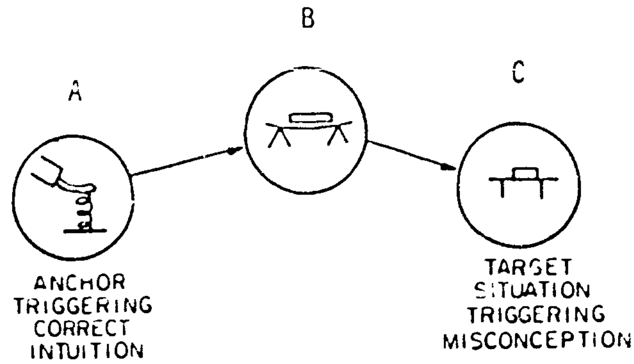

Figure 1

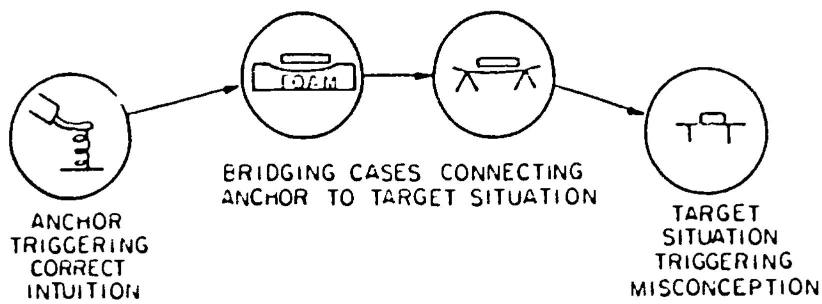

Figure 2

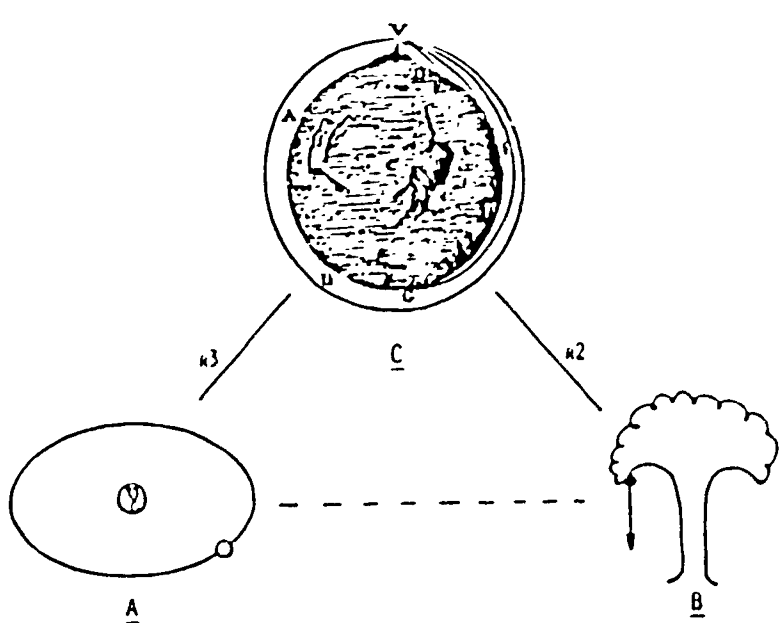

Figure 3

		Average Pretest Score	Average Posttest Score	Average Gain
Control n = 50		5.62 (29.6%)	8.00 (42.1%)	2.38 (+12.5%)
	s.d =	(2.44)	(3.13)	(2.83)
Experimental n = 82		5.63 (29.6%)	14.56 (76.6%)	8.93 (+47.0%)
		(2.38)	(2.90)	(2.84)

Experimental group had larger gain ($t = 12.72$, two-tailed, $p < .00005$).

Table 1

		Average Pretest Score	Average Posttest Score	Average Gain
Homogeneous Control Classes n = 23		5.17 (27.2%)	8.26 (43.5%)	3.09 (+16.3%)
	s.d.=	(2.25)	(3.76)	(3.29)
Lower Experimental Classes n = 46		4.83 (25.4%)	13.63 (71.7%)	8.80 (+46.3%)
		(2.07)	(3.03)	(3.30)

Experimental group had larger gain ($t = 6.80$, two-tailed, $p < .00005$).

Table 2

FORCES FROM STATIC-OBJECT EXPERIMENTAL VS. CONTROL

Points Possible = 6

	Pretest	Posttest	Average Gain
Control n = 50	1.14 (19.0%) (1.34)	2.58 (43.0%) (1.54)	1.44 (+24.0%) (1.39)
Experimental n = 82	1.13 (18.8%) (1.16)	4.83 (80.5%) (1.02)	3.70 (+61.7%) (1.35)

Experimental group showed larger gain ($t = 9.15$, two-tailed, $p < .00005$)

FRICTION FORCES - EXPERIMENTAL VS. CONTROL

Possible Points = 4

	Pretest	Posttest	Gain
Control n = 50	1.08 (27.0%) (0.778)	1.58 (39.5%) (0.835)	0.50 (+12.5%) (1.05)
Experimental n = 82	1.10 (27.5%) (0.795)	2.72 (68.0%) (1.10)	1.62 (+40.5%) (1.25)

Experimental group showed larger gain ($t = 5.5$, two-tailed, $p < .00005$)

DYNAMIC THIRD LAW: EXPERIMENTAL VS. CONTROL

Points Possible: 6

	Pretest	Posttest	Gain
Control n = 50	1.26 (21.0%) (1.14)	1.42 (23.7%) (1.64)	0.16 (+2.7%) (1.68)
Experimental n = 82	1.12 (18.7%) (1.06)	4.50 (75.0%) (1.48)	3.38 (+56.3%) (1.53)

Experimental vs. control ($t = 11.03$, two-tailed, $p < .00005$)

Table 3