1-1-1987

Using analogies and examples to help students overcome misconceptions in physics : a comparison of two teaching strategies.

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USING ANALOGIES AND EXAMPLES TO HELP STUDENTS OVERCOME MISCONCEPTIONS IN PHYSICS: A COMPARISON OF TWO TEACHING STRATEGIES

A Dissertation Presented

By

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Submitted to the Graduate School of the
University of Massachusetts in partial fulfillment
of the requirements for the degree of

DOCTOR OF EDUCATION

September 1987

Education

Research Supported by the

National Science Foundation

Project Number MDR-8470579

Contract Number 5-22750

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ACKNOWLEDGEMENTS

Particular thanks go to the members of my dissertation committee. To Klaus Schultz, for sharing his expertise in the theory and practice of education, and for being so encouraging and supportive throughout; to John Clement, whose insight into cognitive processes and skill as an educational researcher have been a continuing inspiration; and to Arnie Well, for sharing his expertise on the intricacies of experimental design.

I would also like to take this opportunity to thank many of the people who have given a great deal of support, friendship, encouragement, and guidance during my time as a graduate student. I would first like to thank my wife, Michele, for her support, for putting up with many lonely nights as a "graduate school widow," and for her help with the endless details involved in putting a dissertation together. I would also like to thank our housemates Michael and Betsy and their children Heather and Megan for their friendship and for keeping Michele from getting too lonely. Thanks also go to my parents, Harvey and Virginia, to my sister and brother-in-law, Sue and Ken, and to Michele's parents, Mike and Winnie, for their continuing support and encouragement.

ABSTRACT

USING ANALOGIES AND EXAMPLES TO HELP STUDENTS OVERCOME MISCONCEPTIONS IN PHYSICS: A COMPARISON OF TWO TEACHING STRATEGIES

SEPTEMBER, 1987

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Analogies and examples from students' experience are frequently cited as important to teaching conceptual material. However, little research has been done concerning the best use of concrete examples in attempts to remediate misconceptions. This study was conducted in order to explore the effects of an experimental analogical teaching method which uses a connected sequence of "bridging" analogies, compared with a more standard teaching-by-example technique. Both methods encouraged students to become actively involved. In both cases the target concept involved the common misconception that static objects are unable to exert forces.

In two studies, an interviewing and a written instrument study, a total of 130 students interacted with a written explanation employing either the experimental or the more standard teaching technique. The control students worked through a description of Newton's third law based on a passage in a popular high school textbook and were given an explanation of how the law applies to the simple new example of a table

pushing up on a book resting on the table. A number of the control students simply refused to believe this explanation.

In addition to significant differences between student performance on post questions in favor of the experimental technique, qualitative analyses of student reasoning while interacting with the explanations indicated some important implications for instruction. In order for students to make sense of situations for which they have a misconception, they must draw on and extend existing helpful intuitions rather than simply memorizing counter-intuitive principles. To help students in this constructive effort, first, teachers need to be aware that certain examples they themselves find compelling may not be at all illuminating for the student. Second, even when an example has been found that is compelling to the student, it may not be seen as analogous to the target problem in the lesson, and the analogy relation may need to be developed explicitly. Finally, teachers need to keep in mind the goal of helping students develop visualizable, qualitative, mechanistic models of physical phenomena.

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CHAPTER I

INTRODUCTION

Misconceptions - A Significant Problem

Current research on student learning and understanding in science underscores a significant problem in epistemology: contrary to the commonsense theory of learning which implies that all that is necessary is to open our minds to knowledge flowing in through our senses, learning appears to be the result of a complex interaction between pre-existing knowledge structures and sensory experience. Typically students come to the science classroom, especially the physics classroom, with a number of alternative conceptual frameworks which can inhibit the learning and understanding of certain concepts (see McDermott, 1984, for a review of some recent studies in physics). Many alternative conceptions are both widespread and resistant to change; traditional instructional approaches have often had little impact on them (see Halloun and Hestenes 1985 for a study of wide scope indicating both the adverse effect of misconceptions on course performance and the ineffectiveness of traditional instruction in remediating them). These naive student beliefs have a detrimental effect on problem solving, course performance, and the ability to acquire conceptual understanding of the material.

A number of attempts have been made to deal with the problem of misconceptions, but only a very few studies have examined the use of thought situations (such as examples, analogies, and thought experiments) as a possible means of helping students modify their alternative conceptions. Historically, thought situations have been important in the development of science (cf. Kuhn, 1977a). A prototypical example is Einstein's famous thought experiment about what would happen inside an elevator if the cable were cut. According to Einstein, this thought experiment was crucial in his development of the theory of relativity, a theory which brought about a revolution in scientific thought and gave scientists a new conceptual framework through which to view the world.

The power of thought situations in science education has been little explored. If students are led to consider in some depth carefully chosen thought situations, this may have an impact on the problem of misconceptions. Although the use of analogies and examples is encouraged by a number of educators, very little consideration has been given to exactly how thought situations should be used in the presence of misconceptions. Typically teachers and textbook authors will supplement their didactic presentations with examples and analogies which they themselves have found helpful, but the students may or may not find them illuminating. If the analogies or examples are not particularly helpful, work needs to be done to discover how better to use thought situations.

Purposes of the Study

The purposes of this study are twofold: first, to explore whether students' consideration of thought situations alone (i.e. without additional empirical experiences) can have an impact on their misconceptions; and second, to examine whether different methods of using thought situations have different effects on students' misconceptions and the reasons for these differences if any exist. In order to explore these questions, I examined two methods of using thought situations.

The first method is to treat the thought situations as concrete examples of an abstract principle; here the thought situations are intended to illustrate the principle by examples from the students' experiences. The primary focus of this type of explanation is the abstract principle, with the thought situations serving to show applications of the principle. The student should then be able to apply the principle to other situations which are similar to the examples, such as a target problem for which the student has a misconception.

The second way of using thought situations is to treat them as the primary focus of the explanation. The student is led through a connected sequence of analogies beginning with an "anchor" (a situation for which the student believes intuitively that the accepted scientific answer is correct), through intermediate situations or "bridging analogies," to the target problem (cf. Clement and Brown, 1984). Here the thought situations are intended to help the student apply correct intuitions about an analogous problem to the target problem by

providing a new mental model of objects as springy. Initial investigations of this method drew inspiration from analyses of experts' strategies in attempting to solve conceptually challenging problems (Clement 1982a, 1986a). In these studies some experts were observed to use chains of connected analogies in an attempt to construct more adequate mental models of the problem situations.

Method

To investigate possible differences between the two uses of thought situations, I conducted two studies. The first compared student response to two different written explanations in an interview setting. Although this provided some indication of their relative effectiveness in terms of group differences, the main strength of this first approach was that the interview setting allowed for a close examination of the students' interactions with the explanations. The second study paralleled this first study in that the explanations were identical, but they were administered in a written instrument rather than interview format to include a larger number of students than could be included in the interview study. The comparison of the two explanations in these two settings not only provided some indication as to their relative effectiveness, but it also allowed a close look at student reactions to each way of using thought situations.

CHAPTER II

BACKGROUND

Introduction

In recent years a number of studies have been conducted which investigate student beliefs in science prior to formal instruction. These studies demonstrate a wide range of beliefs about physical phenomena which the students have apparently formed on their own without the benefit of formal instruction.[1] This review will examine a number of studies which explore the effects on students' conceptions of traditional instructional strategies as well as more innovative instructional strategies and will draw some conclusions as to the directions future research and curriculum design efforts might fruitfully take.

A number of areas have been studied in which students express naive beliefs. These include, for example, electricity (Fredette and Lochhead 1980, Cosgrove, Osborne and Carr 1984a), thermodynamics (Erickson 1979, 1980, Wiser and Carey 1983), and chemistry and biology (Helm and Novak 1983) as well as classical mechanics. In this review I will focus on beliefs students express about questions in dynamics, as this has been the area most studied. This focus will allow treatment of central issues in greater depth.

In the area of classical dynamics, students have been observed to possess a number of beliefs which are in contradiction with the ideas of Newtonian mechanics. For example, many students do not believe that a static object such as a table can exert a force upward on an object resting on it (Minstrell 1982), in contrast to the Newtonian view which asserts that there must be a force from the table to balance the force from gravity. Also, many students believe that when two moving objects interact, the larger or more active object exerts the greater force (Maloney 1984), in contrast to the Newtonian view that the forces are equal in magnitude and opposite in direction. A third example is the belief that there must be a force on or in an object in the direction of the object's motion (Viennot 1979, Sjoberg and Lie 1981, Clement 1982b) when in fact the force must be in the direction of the object's acceleration. Reviews of research on students' alternative conceptions in classical mechanics are provided by Driver and Erickson (1983), McDermott (1983), McCloskey (1983a), and McDermott (1984).

The first part of this review will give a brief description of some of the work in exploring the resistance of these beliefs to change under traditional instruction. The second part will review some general teaching suggestions which follow from a constructivist framework, in which the student is viewed as an active constructor rather than simply a passive receiver of knowledge. The third part presents the results of a number of empirical studies in which innovative strategies have been tested to determine their effectiveness in helping students overcome misconceptions.

Review of Related Research

The Problem

Ineffectiveness of Traditional Instructional Strategies

Just as physics is the most highly structured branch of the arts and sciences (excepting perhaps mathematics), physics teaching tends to be the most standardized. Almost invariably the important concepts are presented as formal, usually mathematical, relationships between measurable quantities. These concepts are most often presented in a lecture, frequently with an associated laboratory exercise or classroom demonstration to "bring the point home." Students then practice applying the formal relationships in homework problems. To demonstrate their knowledge of the material students are expected on tests to be able to manipulate the formal relationships in contexts similar to those they encountered in their homework problems. When the material in one section has been "covered," the class then proceeds to the next set of formal relationships. This traditional approach to the teaching of physics rests on two tacit assumptions: 1) The teacher has an almost tangible entity called knowledge or information which the student does not possess, and which therefore needs to be transferred to the student. 2) The student is an essentially empty vessel waiting to receive the knowledge when it is presented (i.e. transferred).

Gilbert, Osborne and Fensham (1982) question the second assumption and identify three views about learning: 1) the blank slate or tabula

rasa view - children are expected to know nothing when they come to science class; 2) the teacher dominance view - the student is assumed to have pre-existing ideas which are easily replaced by instruction; and 3) the student dominance view - the student has pre-existing ideas which resist complete displacement by instruction. Under the last view, the final state in the student's mind after instruction is some mixture of the teacher's science and the student's science. Data follow which strongly support the third view that students have pre-existing ideas which are difficult to displace.

Lochhead (1981) presents some quotes from students which give clear indications of difficulties with the concept of force. These answers were given in response to the question "What is the cause-and-effect relationship between force and velocity." (The correct answer is that a force causes a <u>change</u> in velocity, it does not directly cause velocity. Newton's first law states that in the absence of a net force the velocity of an object will remain constant.)

> As one increases, the other increases, and as one decreases the other decreases.
>
> If the force is constant, the velocity will remain constant. If the force is increasing, velocity will increase. If the force is decreasing, the velocity will decrease.
>
> When the force increases, velocity increases, and when the force decreases, velocity decreases. In other words, force is the cause and velocity the effect.

These quotes were in response to a quiz given immediately after a lecture on dynamics in which the misconceptions represented by the quotes had been explicitly discussed and emphatically rejected as

incorrect.[2] Further, the lecture came after several weeks of laboratory work which prepared the students to think clearly about dynamics.

This somewhat anecdotal evidence of the resilience of misconceptions under traditional instruction is supported by Clement (1982b) who found strong evidence for resilience of what he terms the "motion implies a force" misconception. To investigate this misconception, he tested college physics students on a problem requesting them to indicate the force(s) on a coin in flight. Before instruction, the error rate in a college physics course on the coin problem (a course in which most students had already had high school physics) was 88%. After instruction (i.e. one semester of university mechanics) the error rate was only down to 70%. Other problems designed to draw out the velocity implies a force misconception revealed equally disturbing results.

In another study of beginning college physics students, Champagne, Gunstone and Klopfer (1985) found that about 80% asserted that heavy objects fall faster than light objects in a vacuum, even though about 70% of the students had had high school physics. Further, those who had had high school physics did not do significantly better than those who had not. Caramazza, McCloskey and Green (1981) found that in answering a problem about the shape of the trajectory of a pendulum bob when the string is cut, only 33% of those students who had had high school and/or college physics could answer correctly. Of particular interest is the fact that the vast majority of those answering incorrectly indicated that if the string were cut when the bob was at its lowest point (the

center of the swing) the bob would fall straight down. In follow-up interviews students indicated that they knew that the bob would be moving at that point.

Halloun and Hestenes (1985) gathered into one diagnostic test a number of questions reported in the literature known to evoke misconceptions. They found that in a university calculus based physics class, the diagnostic scores moved from 50% to only 65% as a result of a full semester of instruction in mechanics. Further, this gain was remarkably independent of instructor. Of the four instructors represented, one was a theorist who emphasized careful definitions and logical arguments, one incorporated many demonstrations and strove "especially to help students develop physical intuition," one emphasized solving example problems in class, and one was an inexperienced teacher who followed the book closely. The post-test scores of students in their classes differed by no more than 1%. The widely varying styles of presentation seemed to have little differential effect.

Clement (1983b) speculates that a possible explanation for the resilience of students' alternative conceptions in certain areas is that they form a system of mutually supporting alternative conceptions rather than a collection of isolated ideas. If this is the case, the entire system of ideas must be replaced with a new system of ideas. Such a change is reminiscent of Kuhn's (1970) idea of revolution in science when an old paradigm is replaced by a new paradigm. (Put briefly, a paradigm is a set of mutually supporting assumptions and implicit operating principles of a group of scientists).

As a somewhat depressing final note in this section on the ineffectiveness of traditional instruction, Arons (1981) states that he finds all the misconceptions which students hold widely prevalent among high school physics teachers as well. Thus the indications are clear that traditional instruction, with its emphasis on a formal, quantitative approach to teaching physics, is having little effect on the alternative conceptions which students have before instruction.

But there is still a glimmer of hope for traditional instruction. If the presence of misconceptions were to have little real effect on students' ability to solve problems and perform well in physics courses, their presence may not be a real concern. However, this hope fades for two reasons. First, for the majority of students who take introductory physics as a terminal course, the objective is not to prime them for future physics courses in which formal quantitative methods assume paramount importance. Rather, along with increased facility with formal reasoning, it is hoped that their experience with physics will give them increased _conceptual_ understanding of the physical world, an understanding which they can apply in real-life situations as doctors, lawyers, airline pilots, auto mechanics, etc. Second, as the following studies indicate, misconceptions _do_ have a significant effect on problem solving performance and overall course performance.

Effect of Alternative Conceptions on Student Performance

Problem solving. Several studies have been conducted investigating the differences in performance between experts and novices

in solving physics problems (Larkin, McDermott, Simon and Simon 1980, Chi, Feltovich and Glaser 1981, Larkin 1983). The consensus of these studies is that novices move directly from the verbal statement of the problem to the equations which they feel are applicable. In contrast, experts first construct a qualitative conceptual representation of the problem (either externally as a diagram or internally), and then choose more formal and quantitative solution methods such as equations based on that representation.

In relating these studies to the work in misconceptions, Champagne, Gunstone and Klopfer (1983a) hypothesize two different problem solving processes for experts and novices. The expert uses a "comprehensive and integrated motion-of-objects schema" to interpret the problem statement, derive a qualitative analysis, and finally to select an equation. Novices, however, use both their naive motion-of-objects schemata and their motion-of-objects schemata derived from physics instruction to interpret the problem statement. They then use their motion-of-objects schemata derived from physics instruction to directly select an equation, skipping the qualitative analysis stage. The instructional implications of this hypothesis are two-fold: 1) students should be given help becoming skilled at qualitative analysis, and 2) students should be helped to restructure their motion-of-objects conceptions into the comprehensive and integrated conception of the expert.

Heller and Reif (1984) present a study indicating what student performance <u>could</u> be if they were to internalize some of the expert strategies. In this study, Heller and Reif compared problem solving performance under two different conditions. 1) Control - subjects given

no guidance, and 2) Guided by model - subjects given hints such as "look at all the points of contact in determining forces in force diagrams." Subjects guided by the model answered problems correctly 90% of the time versus only 20% of the time for the control group, indicating these hints concerning problem representation would aid problem solving if internalized by students.

Larkin (1983) reports on a similar study in which one group of students received training in ways of representing simple circuits and another group received training in systematic application of principles. The group receiving the representation training did "strikingly and significantly" better. These studies indicate that ability to effectively represent problem situations is crucial to success in problem solving. Since students' alternative conceptions are a block to forming effective qualitative conceptual representations of problem situations, they present an effective block to problem solving performance.

Performance in courses. Champagne, Klopfer and Anderson (1980) and Halloun and Hestenes (1985) conducted studies examining the effect of the presence of misconceptions on course performance. Champagne et al. considered the predictive effect on course performance of misconceptions about the relationship of force and motion. Although the misconceptions score was not a "strong" predictor of success, they found a significant correlation between the misconceptions score and course performance. Halloun and Hestenes, in a study of impressive scope, gathered into one mechanics diagnostic test a number of questions reported in the literature known to evoke alternative conceptions in

both kinematics and dynamics. They administered the test to a number of calculus and non-calculus based college physics classes, and they found that the score on the diagnostic test was the best single predictor of achievement in the course, superior to a math pretest and combined prior physics and math courses.

Thus, a serious problem exists. To meet the needs of the majority of students, introductory physics courses must stress conceptual understanding of the material. However, students come to class with beliefs which are in contradiction with the fundamental concepts of physics and which are difficult to displace. These beliefs affect physics problem solving ability, course performance, and, almost by definition, conceptual understanding of the material.

Suggestions for Change

Presence of Misconceptions Requires a New Approach

Commonsense theory of learning and instruction. Traditional instructional approaches rest on what Karl Popper has called the commonsense theory of knowledge. This theory is quite simple and intuitive - information comes to us through our senses, and we absorb that information into our minds. It then becomes part of our store of knowledge. It is not particularly important whether the mind is viewed as initially empty or as initially containing some knowledge. What is important is what governs the increase of knowledge. Under this theory, "If you or I wish to know something about the world, we have to open our

eyes and look round. And we have to raise our ears and listen to noises, and especially to those made by other people. Thus our various senses are our sources of knowledge - the sources or the entries into our minds." (Popper 1972, p. 60) This theory has enjoyed enormous popularity among philosophers since the time of Francis Bacon, and it is still seen by many as the "scientific" view of knowledge.

Constructivist approach to learning and instruction. If the commonsense theory of knowledge were correct, then one would expect that students would either not have the misconceptions that have been documented, or that these "mis-inductions" of experience would be easily replaced by new and better knowledge entering their minds through instruction. Because neither of these is the case, a more sophisticated epistemology is called for, one which considers the interaction of internal knowledge structures with sense experience. A number of authors describe such a constructivist position (Driver and Easley 1978, Koplowitz 1980, Osborne and Wittrock 1983, Driver and Erickson 1983, Pope 1982, Pope and Gilbert 1983).

Driver (1984) outlines four points of a constructivist perspective. 1) "What is in the learner's head matters." In other words, it is not just the environment surrounding a learner which determines learning, but the existing conceptions and motivations also play a crucial part by influencing student interpretations and explanations, problem representations, and attention to aspects of empirical experiences. 2) "Making meanings is about making relationships." These relationships may be either explicit (as in the case of axiomatic systems) or implicit (as in the case of expectations of physical events). 3) "Learners

actively construct meanings." In her discussion here, she sees analogy playing a central role in the "making sense" of new situations by drawing on past experience. 4) "Students are responsible for their own learning." Students must actively construct meanings from (i.e. make sense of) new experiences in order for learning to occur. A constructivist perspective on learning carries with it the implied principle that teachers must function not primarily as presenters of material, but rather as facilitators helping their students actively grapple with the material.

Constructivist Suggestions for Teaching to Overcome Misconceptions

Non-constructivist solution. In discussing how to avoid misconceptions in mechanics, McClelland (1985) suggests that increased clarity will substantially reduce the problem (cf. Warren 1979). As an example, he suggests a careful definition of a "body:" "When viewed from the center of mass of the system everything involved in an interaction whose momentum change is in the same direction constitutes one body. Everything whose momentum change is in the opposite direction constitutes the other body" (p. 161). So, for instance, if a boy and a girl sit facing each other on carts with a rope between them and the girl tugs on the rope, then her arm, the rope, and the boy accelerate in one direction while the rest of her body accelerates the other way.

Besides considering for each specific example of "clarity" whether it would be clearer to the student than another way of presenting the material (what clarifies a situation for the physicist may or may not

for the student), this raises a more fundamental question about the process of teaching. Given the uniformity of post test scores on Halloun and Hestenes' (1985) diagnostic for four different professors (with varying levels of clarity and use of examples) it seems unlikely that increased clarity or other alteration of the presentation of material alone will have much effect if the model of teaching is the "teacher as presenter" rather than the constructivist "teacher as facilitator" model. Under the latter model, the teacher is viewed as facilitating the students' active construction of meaning rather than simply pouring information into the students' heads. Following are presented some techniques which have been suggested as methods of actively engaging the student.

Socratic dialogue. The literature contains a number of suggestions as to how best the teacher (or the designer of computer assisted instruction) might facilitate the student's active construction of meaning. Socratic dialogue, a dialectic exchange between teacher and student, is advocated by a number of authors as stimulating such active construction (Collins 1977, Arons 1981, McDermott, Piternick and Rosenquist 1980, Champagne, Klopfer and Gunstone 1982). Where such dialogue is impractical because of the large student teacher ratio, student-student dialogue has been suggested as a way of requiring active participation by both the "problem solver" and the "listener" (Lochhead 1983, 1979).

Murray, Clement and Brown (1986) describe the possible use of the computer as a Socratic "case-based tutor," a tutor which guides the student through a network of analogies to help them "bridge" from a

conceptually intuitive situation to a counter-intuitive situation (Clement and Brown 1984, Brown, Clement and Murray 1986). Arons (1984) describes several computerized Socratic dialogues which guide students in reasoning about physical phenomena. Like the case-based tutor, these are essentially routines which branch appropriately based on student input. Any "intelligence" in the software is simply the careful structuring put there by the designers. This is as contrasted with several intelligent tutors in other areas such as plane geometry and LISP programming which are "generative" tutors (Anderson, Boyle, and Reiser 1985) capable of adjusting to student input "on the fly" based on a model of student thought processes.

Class discussion. In a classroom situation, class discussion is a technique which has the flavor of a Socratic dialogue and retains many of the benefits. This is a technique which has the advantage over Socratic dialogue of student-student interaction as well as teacher-student interaction (Nussbaum and Novick 1981, Minstrell 1982, Champagne, Gunstone and Klopfer 1983b, Clement 1986b). Disadvantages are that some students may still remain passive, and some may feel inhibited from expressing confusion or disagreement due to social factors. In order to reduce the passivity of some students, techniques have been used such as having students vote at key points during the discussion (Minstrell 1982, Clement 1986b). To reduce the social inhibitions, Minstrell suggests efforts to create "an engaging, free thinking, free speaking social context, in which students are encouraged to articulate their beliefs."

The focus of Socratic dialogues or class discussions could be either empirical demonstrations or thought experiments. The advocates of empirical demonstrations are too numerous to list (who is not an advocate?) but the use of thought experiments is less widespread. Kuhn (1977a) and Helm and Gilbert (1984) discuss the importance of thought experiments in the development of scientific ideas. Brouwer (1984) suggests the consideration of qualitative thought situations in a classroom discussion environment as a useful introduction to new material. However, he also states that in his opinion, even professional scientists frequently feel uneasy about this approach because they sense that their own conceptions are not as mature as they could be. Clement (1986a) advocates the use of thought situations in classroom discussions, and in particular, comparing thought situations about which the student has differing intuitions, but which the physicist sees as analogous.

Hands-on experiments. A frequently cited suggestion is that of hands-on empirical experiences. Renner (1984) describes a naturalistic study in which students showed a strong preference for actually gathering the data themselves (as opposed to a teacher demonstration or having pre-collected data given to them). However, Bates (1978) presents a review of studies investigating the cognitive advantage of laboratory work versus no laboratory work. The consistent conclusion is that there is no advantage of laboratory work. Champagne, Gunstone and Klopfer (1985) suggest this result is not surprising, given that the laboratory is frequently seen by students as a place to concentrate on

interacting with strange equipment, collecting data, and above all, getting the correct answer.

However, if handled correctly, hands-on laboratory experiences have the potential to be very effective. Dykstra and Minstrell (1984) outline five points for the effective use of hands-on empirical experiences in teaching to overcome misconceptions: 1) help students clarify their initial beliefs to prepare them for conceptual conflict, 2) have them check their beliefs against an experiment, 3) allow THEM to resolve the discrepancies, 4) begin with direct experiences and build toward more abstract understanding, and 5) provide repeated opportunities to reuse the new ideas in new contexts.

An alternative to actual empirical experiments is that of using the computer to simulate physical events. Champagne and Rogalska-Saz (1982) warn against going overboard with simulations, arguing that simulations should be used only when alternative empirical means are impractical. However, there are a sufficient number of situations in which this is the case to make this an exciting approach (diSessa 1982, 1985, Hollifield 1982, Hewson 1984). White (1984) discusses six design principles for computer simulations or "microworlds:" 1) represent the phenomena of the domain clearly, 2) eliminate irrelevant complexities, 3) focus students on aspects of their knowledge that need revising, 4) facilitate the use of problem solving heuristics, 5) encourage the application of relevant knowledge from other domains, 6) encourage better ways of representing and thinking about the domain.

DiSessa (1985) discusses "mega-microworlds" (a group of several individual microworlds with a common thread), and "textured microworlds"

(microworlds capable of making principled interventions, of "debugging" student core intuitions, what he calls p-prims, cf. Brown and VanLehn (1980) and VanLehn (1981)). Tinker (1983) describes another potentially powerful use of the computer in science laboratories - microcomputer-based instrumentation. With this use of the computer, the student interacts with actual physical systems, but the computer is used as a data taking tool to remove the drudgery and help make the experience more immediate.

Empirical Studies

The preceding section described several suggestions of methods which it is hoped will help the student actively construct new understanding of a domain. All of these methods have been tried in some form, and following is a description of a number of studies which have attempted to explore changes in student performance or understanding after some type of intervention.

Driver (1973) in a pioneering study examined in detail the learning of four 8th grade students in a discovery learning environment in science. The three learning units examined were a unit on balancing, a unit on springs, and a unit on force and motion. The role of the teacher in this environment was to suggest possible experiments (students were encouraged to invent their own), lead class discussions, and engage students in dialogue about their experimental results and possible interpretations. She made some very interesting observations about students' semi-quantitative or direction-of-change reasoning, but

the overall conclusion, from the standpoint of the effectiveness of the instructional strategy, was that there was little conceptual change as a result of the learning environment. She summarizes the results as showing that counter examples and conflicting evidence did not, by themselves, encourage a change in pupils' thinking. When an alternate theory was presented, either by the teacher or another student, which better accounted for the data, it was not necessarily understood but rather accepted and learned at a verbal level.

In the unit on springs, the students engaged in some discussions about whether static objects, such as a lab bench, could exert forces. Minstrell (1982) confronted the same question in a classroom discussion environment. After discussing what the word "force" means (the consensus was force as a push or pull) he asked the question about whether a table exerts a force upward on a book resting on it. Initially about half the class maintained that there was an upward force, while the other half maintained that there was a downward force only. Following this he presented several situations which also involved an upward force but which were much more intuitive for students, such as a book resting on the hand, a book hanging from a spring, and a paper clip hanging from a spring. As a final demonstration, he reflected a light beam off of a table and stepped on and off the table to show the slight flexibility of the table by the deflection of the beam. After this sequence of demonstrations, twenty five of the twenty seven students in the class expressed a belief in an upward force from the table.

Clement and Brown (1984) explored a similar strategy in a tutoring interview environment. They present a case study of a humanities graduate student who was initially incredulous at the idea of an upward force from the table. After presenting a number of thought situations for her consideration which bridged the "conceptual distance" from the situation of a book on the hand (for which she felt there would be an upward force) to the target situation of the book on the table, she "agreed not just for the sake of agreeing" that the table exerts a force upward on a book resting on it. The study from which this case study was drawn is discussed in more detail in the section on previous studies by this author.

The strategy of using intermediate or "bridging" analogies described above was used as the guiding principle by a group of physics educators at the University of Massachusetts in designing classroom curriculum materials for the areas of forces from static objects, friction, and Newton's third law (static and dynamic). In comparison with control classes, the classes using the experimental lessons performed significantly better on a diagnostic test examining conceptual understanding in the above-mentioned areas (Clement 1986b).

Gunstone, Champagne and Klopfer (1981) describe a study in which twelve junior high school students participated in seven instructional sessions designed to improve their conceptions of the relation between force and motion. The predominant approach used in this study was group discussions of Demonstrate, Observe, and Explain (DOE) tasks, as well as some use of hands-on experiences and a computer simulation. The DOE tasks involve students making a prediction, explaining the basis of the

prediction, observing the results of a demonstration, and reconciling, if necessary, the prediction and the observation. The instruction was not very successful; most students had not abandoned an "Aristotelian view" by the end of the sessions. However, their feelings toward the inquiry remained positive throughout the sessions. As several of the DOE tasks involved objects falling through media, the investigators became conscious of the need for an improved understanding of the concept of density. (See Hewson and Hewson (1983) for a report of an approach indicating some success with overcoming misconceptions about density).

Champagne, Gunstone and Klopfer (1983b) report on a similar study in which two very different groups were subjected to a discussion oriented learning environment for several sessions. The methods employed were very similar to those described above (e.g. discussion of simple experiments such as dropping balls of different masses) and seemed to have little effect with gifted middle school students. However, the discussions seemed to have an effect on changing the cognitive structures of pre-service high school teachers who were non-physics major science graduates (see Gunstone 1980 for a report on a similar study which had a positive effect with 11th grade students). All of the pre-service teachers said two objects of different weight would fall in equal times, but they said this because they thought the force on them would be the same. Each student kept a journal, and after a long (5 hour) session in which they discussed various DOE tasks addressing the reasons for equal falling times, one student wrote this.

> I'm shattered! Didn't realize how devastating it could be to have a deep rooted belief proved wrong. Can I blame my physics teacher? It would be all right if some dummy didn't pose a question which could be used to support the opposite argument. Seriously though, very instructive. I don't know if I'm going to last the distance. I'm mentally exhausted after each session and the effort to hold out when I'm wrong is draining. Great fun so far even if I hate it at odd times. (Champagne, Gunstone and Klopfer 1983b, p. 19.)

Dykstra and Minstrell (1984) and Minstrell (1983b) describe an approach to teaching Newton's first two laws of motion which seemed to have an impressive effect on student performance on conceptual questions. Following a unit on kinematics and Minstrell's (1982) "at rest" lesson, students were asked to describe what it is about the forces on a cart that cause it to move at a constant velocity. The overwhelming response was that a constant net force is required to keep the cart moving. After this, students engaged in a hands-on lab activity in which they observed the results of a constant force on a dynamics cart. Many expressed surprise (and dismay) that a constant force produces acceleration rather than constant velocity.

After this, a class discussion was held in which a student usually asked the question "if a constant force causes a constant acceleration, then what explains constant velocity?" (One interesting feature of this approach is that it treats the constant acceleration case, governed by Newton's second law, before the constant velocity case governed by Newton's first law.) Following hypotheses such as decreasing force causing constant velocity (not upheld by the data) usually the hypothesis was put forth timidly that perhaps no force is necessary for constant velocity. This sequence was followed by a more standard presentation of Newton's laws, and the concept of constant velocity not

requiring motion was revisited (cf. Arons 1981) in further class discussions in other contexts such as circular motion.

Three comparisons are made in these papers. First, Minstrell compares the performance of his class taught with this method with the performance of his previous classes taught with more traditional methods. With a standard instructional sequence, student performance on conceptual questions concerning the relationship between force, velocity and acceleration rose from 2% correct before instruction to 29% at the end of the year. With a standard sequence plus an extra two weeks devoted to treating with special care the logical argument for constant velocity in the absence of a force, the post-course results rose to 41%. However, with the experimental sequence, post results rose to 79%, with 95% answering consistently and correctly questions regarding the relationship between force and constant velocity.

In the second comparison, another physics teacher in the same school tried the experimental sequence. Directly afterwards, his students performed at about the same level as Minstrell's. However, at the end of the year, his students had shown some regression. Minstrell attributes this to the lack of revisiting the concept in other contexts. In the third comparison, the sequence was also tried with ninth grade students. With these students it was much less successful in that the students seemed unable to entertain the idea that the force was constant but the cart was accelerating. Minstrell hypothesizes that they were so driven by their preconceptions that their observations were distorted by their beliefs.

White (1984) describes a computer microworld which has a significant effect on students' ability to answer conceptual questions involving Newton's laws. The microworld makes use of a "dynaturtle" (diSessa 1982) environment, and is structured as a series of video-game-like exercises in which the user has the goal of making a rocket execute maneuvers in a two dimensional plane by firing engine bursts in various directions. The most interesting result is that the games had a transfer effect. To a question asking how to get the rocket to move in a circle, significantly more of the students who had interacted with the microworld were able to answer correctly (continuously fire toward the center of the circle) even though this was not one of the exercises. Hewson (1984) describes a similar microworld in one dimension, but he presents no results of its effectiveness.

Previous Studies by this Author

Original Tutoring Interviews - Forces from Static Objects

Clement (1982a) examined the role of analogical reasoning in expert problem solving. This study showed that using an analogy can change an expert's understanding of a problem situation by changing the conceptual model he or she uses to think about the situation. This suggested that the right analogy might allow students to overcome a deep misconception by helping them to change the conceptual model they use to think about a physical phenomenon. For example, many students find it difficult to conceive of certain inanimate, "rigid" objects as

capable of exerting a force. When asked about a book at rest on a table, they will argue strongly that the table is not exerting an upward force - it is simply "in the way" stopping the book from falling to the ground.

Instructional Strategy

In this study, ten students were tutored about the book on the table situation in an interview context. Of these, six initially maintained that the table does not exert an upward force on the book (most expressing strong conviction in this belief). All six came to believe in an upward force from the table by the end of the interview. The instructional strategy, developed by John Clement and myself, is described below.

The instructional strategy uses analogical reasoning in an attempt to help students overcome "deep" misconceptions in physics. In this strategy a misconception is combatted by appealing to other intuitions already existing in the student's memory which are essentially Newtonian. The assumption is that even though the student has one intuition that tells him that a table cannot push up on an object, he may have intuitions that predict upward forces in other situations, such as holding a book on an outstretched hand. In this case the book on the hand is called the anchor situation, and the book on the table is called the target situation. If this is the case, the two competing intuitions may perhaps be brought into conflict if the student can be brought to see an analogical relationship between the target and the

anchor. We hoped that this conflict would break down the misconceived dichotomy of things that can exert forces and things that cannot and allow for the transfer of intuitive understanding from the anchor to the target.

In order to make the tone of the tutoring interaction as non-authoritarian as possible, the subjects were told that the interviewer would adopt a "devil's advocate" stance, and the subject was asked to maintain his views unless it seemed reasonable to him to change them. This stance allowed the tutor to challenge the views of the subject in a non-threatening way.

The first step or tactic in the instructional strategy is to draw out the misconception in as clear a way as possible. This is usually done by asking a question known to evoke a misconception and asking the student to commit himself. The next step is to suggest an analogous case (such as a hand holding up a book) that the instructor feels will appeal to the subject's intuitions. Hopefully the subject's memory of the muscular effort needed to hold up a book will convince him that the hand pushes up. If the subject does not have the intuition of an upward force in this situation there are three possible courses of action: 1) let the subject try holding an actual book in his hand (an <u>empirical experience</u>), 2) suggest the <u>extreme case</u> of a very large book or many books on his hand, or 3) ask about a different situation (i.e. search for a <u>different anchor</u>) such as pushing down on a bedspring.

Once the subject does believe in the force acting up in the analogous case, he may still be unconvinced that there is a valid

analogy relation to the original case of the book on the table. When this occurs four subsequent tactics can be attempted singly or together.

(1) Ask the subject to make an explicit comparison between the original case and the analogous case. The question could be phrased as follows: "In (the anchor) you say there is an upward force, but in (the target) you say there is not. What's the difference that makes you say there there is a force in (the anchor) but not in (the target)?" This is in effect asking the subject to examine his intuitions about the two situations and articulate the essential difference(s). Even though the subject may have a difficult time putting his intuitions into words, the interaction of the two situations, each in the context of the other, can begin to draw out important characteristics which give rise to different intuitions in the anchor and the target.

(2) The second tactic is to attempt to find a third case in between the original case and the analogous case. This is termed a bridging analogy. For example, one might propose the idea of a book resting on a spring (a bridge) which shares some features of the book on the table (the target) and some features of the book on the hand (the anchor). This can have a disturbing effect on the equilibrium of the student. For example, many students see several crucial differences between the book on the table and the book on the hand. One involves a non-living object, one a living person. One involves a non-volitional object, one a volitional being. One has potential movement, one is just a rigid barrier. One involves leverage (the outstretched arm), one does not. For some students, the book on the spring begins to break down the comfortable dichotomy of pushers and barriers because it shares some

qualities of the table, yet it brings out the intuition of an upward force.

(3) A third tactic involves making an explicit transformation between the target situation and the anchor or the bridge. For example, a subject may believe that a ruler suspended between supports will bend when a weight is placed on it, but not believe that a table will bend with a weight on it. If the student is asked to imagine placing a weight on thicker and thicker rulers (or thinner and thinner tables), he may be led to believe that the table bends slightly.

Each of the above tactics can be used in a recursive fashion. For instance, if the subject believes in an upward force in the anchor situation of a book on a hand, but does not believe in an upward force in the bridge situation of a book on a spring, the book on the spring can be considered the new problem or target situation and any or all of the above three tactics can be applied to break down the new misconceived dichotomy.

(4) A fourth tactic involves the introduction of a model of matter which puts further pressure on the force/no force dichotomy. In this model the table is composed of molecules which are connected to other molecules by bonds which are springy. Thus the table can be seen to be springy at a microscopic level. This model is introduced if the subject is convinced in an upward force from a flexible object but continues to maintain that the table is rigid.

Summary

The protocols provide evidence for the subjects making some progress in changing their ideas at a fairly deep conceptual level. The main principles used in this approach were (1) Socratic tutoring - in which questions posed to the student encouraged her to become actively involved in learning; (2) Using key examples to activate useful intuitions possessed by the student; (3) building on and extending those intuitions by using analogical reasoning, and in particular, using the strategy of "bridging analogies" that has been observed in the solutions of experts problem solvers. In the following study, the above strategy was employed in several other content domains.

Tutoring in Other Domains

In the spring of 1985, five high school juniors who had not yet taken physics were tutored in four domains using a bridging tutoring strategy. These domains were: 1) forces from static objects, 2) dynamic third law - explosions, 3) dynamic third law - collisions, and 4) friction. This was the first attempt to try the analogy based teaching strategy with preliminary pilot materials in several different content domains.

Forces from Static Objects

Three of the five students had previously taken a diagnostic test and were acquainted with some of the particular questions asked. This had a definite effect in the first domain of forces from static objects. Two of these three mentioned they had changed their minds about the particular question asked (the existence of a force upward on a book resting on a table) as a result of the diagnostic. One mentioned asking a friend who was taking physics, and the other (a very advanced student) changed his mind after thinking about it on his own. Only one of the five tutored initially felt the table did not exert an upward force, and he came to believe in the upward force by the end of the tutoring.

Explosions

In the second domain of explosions, the particular question concerned comparing the speeds with which two skaters of equal mass on a frozen pond separated when one pushed on the other's chest. Four of the five answered this incorrectly, and only one changed as a result of the tutoring. This ineffectiveness may be attributable to the "brittleness" of the anchor situation used to ground the lesson in the student's physical intuitions. The anchor was the symmetric situation of two carts with a spring between them not attached to either one. When asked how fast the carts would move apart when the rope holding them together was cut, all said they would move apart at equal speeds.

However, the addition of a tiny drop of glue to one end of the spring attaching it to one of the carts changed the answer for three of the students. The spring was now part of one of the carts. Thus the anchor was "brittle" in the sense that breaking the symmetry in any way destroyed its effectiveness.

Collisions

In the third domain of collisions, the target question concerned the force exerted on a stationary eight ball by a moving cue ball. Every one of the five answered with high confidence that the moving ball exerted the greater force. The situation used as a possible anchor in this case was that of Mr. T tied to the front of one railroad cart running into another stationary car. Four of the five thought he would feel the same force whether his cart ran into the other one, or the other one ran into him. In this case the anchor was perceived as analogous to the initial problem by all the students, and this produced conflict as their intuitions gave different predictions in the two situations. Two of the four resolved the conflict by deciding that the cue ball and the eight ball would feel the same force, but the cue ball would exert the greater force because it was bringing the force to the collision. This force would then be transferred to the eight ball, and during this transfer, each would feel an equal force. The other two of the four for whom Mr. T was an anchor ended the session confused, unsure which way to go. The student for whom Mr. T was not an anchor was apparently unmoved by the session.

Friction

In the fourth domain, the particular question concerned the existence and direction of a force from the floor on a shuffleboard puck that would affect its motion. Three of the five gave an incorrect answer, either that there was no force acting or that it acted in a direction other than that opposing the puck's motion. The anchor in this situation was that of two hairbrushes slightly intermeshed and pulled across each other. This was an anchor for all three of the five who initially answered incorrectly, as they felt the moving brush would feel a force in a direction opposite to its motion. Of these three, two came to the correct answer at the end for the shuffleboard puck.

Conclusions

Initial indications were promising concerning the effectiveness of a bridging tutoring strategy for helping students overcome misconceptions in mechanics. Not including the skaters problem (for which the anchor was "brittle," thus sabotaging the method), nine incorrect answers were represented overall. Of these nine, four were changed to correct answers as a result of the tutoring, two were changed to partially correct answers (each ball feels the same force in a collision but the cue ball exerts the greater force), and two remained in a state of conflict, unsure about the equality of forces in the collision problem. Thus, in eight of the nine cases, there was

significant movement away from the student's initially incorrect answers as a result of the bridging tutoring strategy. This study provided input to the development of classroom lessons described elsewhere (see Clement 1986b), but we also felt that the method itself could be fruitfully explored in greater depth. As an effort in that direction, I conducted the following study to compare a written form of the bridging analogies method (which demonstrates the causal agent responsible for the table's force - its springiness) with another method.

Comparison of Logical and Causal Explanations

This study was designed to explore the effects of two different types of explanations - logical and causal. A logical argument is an argument that the result must be true - in essence an argument based on form or structure with no concern for specific content. A causal argument, on the other hand, demonstrates the truth of a statement by showing the agents which make the statement true. The tutoring provided no data to test the relative effectiveness of logical and causal explanations. In order to explore this comparison a written instrument was designed to be distributed to a large number of students so that statistical comparisons could be made between a one page logical explanation and a one page bridging causal explanation.

Each student answering the table problem incorrectly received one of two possible explanations - a bridging causal explanation, or an explanation arguing on logical grounds that the table must exert an upward force (in brief, the table must exert an upward force or the book

would fall to the ground). To evaluate the effectiveness of the interventions, two measures were employed: 1) performance on transfer questions, and 2) the student's own subjective rating of how much sense it made to her that a table does or does not exert a force. The written tutoring instrument was administered to six chemistry classes at a New England high school. Of the 104 students who participated, 74 indicated the belief that the table is not exerting an upward force on a book at rest on it. Of these 74 students, 37 received logical explanations and 37 received bridging explanations.

There were no statistically significant differences between the logical and bridging causal explanations on either of the above quantitative measures (transfer problem scores and sense scale ratings). Although this was initially surprising, examination of some of the students' comments indicated an initial bias toward the logical explanation. Before the tutoring, 30 of the 104 students indicated the presence of a force from the table, and of these, 18 were clearly condensations of the logical explanation. Of the remaining 12 explanations, only three gave any indication of the presence of a causal agent as grounds for answering that the table exerts a force.

On further consideration, I realized that this study was not comparing a causal explanation (i.e. an explanation promoting a visualizable causal model) with a non-causal explanation, but rather it was a comparison of two explanations both of which called for causal reasoning. The explanation which I termed the "logical" explanation I would now call an <u>indirect causal</u> explanation in that it calls for the assumption of a causal agent based on the observed effect, in this case

the book's remaining above the ground. As with the causal explanation, which promotes a model of spring compression, the logical explanation may evoke equally powerful and intuitive images of two active sources of force fighting against each other and reaching a stalemate or equilibrium as a result of equal forces, for example arm wrestling or a weightlifter holding up a weight (similar to one of the anchors in the causal explanation, an arm holding up a book). Students using the "logical" argument have since been observed to talk about such images in classroom discussions.

Thus the "logical" explanation was not optimal in the sense of providing a comparison of two explanations, one of which attempted to help the student construct a new mental model and one of which did not. The indirect causal explanation could help students construct the model of the table as opposing or resisting the book's weight, tying into existing student models of equal opposing forces. In order to provide a comparison between an explanation which explicitly tries to help students construct a mental model and one which does not, in the current study the bridging explanation was compared with an explanation which simply provided example support for an abstract principle, Newton's third law. This law could then be applied to the book on the table situation to arrive at the conclusion that the table is exerting an upward force on the book since the book is exerting a downward force on the table. (Of course it could be argued that even this explanation might evoke students' models of active, opposing, equal forces achieving equilibrium, but the explanation does not explicitly try to promote this.)

Conclusions and Directions for Future Research

It is clear that student misconceptions are widespread, resistant to change under traditional instruction, and have a detrimental effect on student performance in physics. It also seems clear that an instructional approach based on the commonsense theory of knowledge is simply inadequate. Knowledge cannot be viewed as a tangible entity which the teacher possesses and can with sufficiently clear presentations pour into the students' waiting minds. However, the picture is not completely bleak. A number of studies mentioned above report significant gains in students' conceptual understanding with the use of innovative teaching strategies. These strategies were based on a constructivist perspective in which the teacher or instructional environment is viewed as a facilitator helping the student to actively grapple with the concepts.

The literature reviewed certainly gives some cause for optimism that the problem of persistent misconceptions is not insoluble. However, the studies reviewed demonstrated some limited successes which were unpredictable. If curriculum development efforts are to be more than the artful manipulation of some general strategies for "actively involving" the student, lesson development needs to be guided by a well developed and coherent theory of instruction. In order to contribute to such a theory, constructivist approaches must be examined closely and in comparison with other constructivist approaches rather than simply in comparison with traditional instructional techniques. In this way

insight may be gained into <u>why</u> certain approaches are effective or ineffective.

The use of analogies, in particular the use of a chain of analogies from an intuitive anchor to a target problem, has been shown in some early studies to be a promising direction for further exploration. One possible direction for this further exploration is that of comparing the relative effectiveness of this instructional approach with another constructivist method using examples. The further exploration of the effect of analogies and examples on students' thinking may provide not only the hope of immediately usable lessons in the form of effective analogical teaching techniques, but may also contribute to the formation of a coherent theory of learning and instruction in the presence of misconceptions.

CHAPTER III

RATIONALE FOR THE CURRENT STUDIES

Research Questions

As mentioned earlier, the purposes of this study are twofold: first, to explore whether students' consideration of thought situations alone (i.e. without additional empirical experiences) can have an impact on their misconceptions; and second, to examine whether different methods of using thought situations have different effects on students' misconceptions and the reasons for these differences if any exist. By comparing two constructivist approaches both making significant use of examples and both encouraging the student to become actively involved, I hoped especially to be able to explore <u>why</u> the different methods of using thought situations were or were not effective.

The two purposes can be stated more precisely in the form of the following research questions. I will divide the research questions into two main categories: product questions which ask about student response to the the explanations taken as wholes, and process questions which require closer examination of student interactions with the explanations.

Product Questions

1) Can thought situations alone bring about conscious conceptual change?

A major thrust in science education is on increased empirical experience in the laboratory. Historically, thought experiments and analogies have played a significant role in the development of scientific thinking, and the question arises as to whether thought situations alone, without the benefit of empirical experiences, can have an impact on student thinking. (If such is the case, I would not advocate abandoning laboratory experience, but rather, supplementing the laboratory experiences with carefully chosen thought situations and qualitative reasoning about those situations.)

2) For the two explanations examined in this study, does the explanation which uses bridging from a thought situation anchor to establish a causal model increase student performance more or less than the explanation making use of concrete examples inductively supporting and illustrating a stated principle?

This study will explore student reaction to and student performance after interaction with one of two explanations which use thought situations in very different ways. One uses them as examples of a formal principle, and the other as parts of a connected chain of analogies from an anchor to a target situation. If student reaction to

and performance after the two explanations is significantly different, this would indicate that care must be taken with the use of thought situations to have the greatest impact on student thinking.

Process Questions

3) When tutoring which uses thought situations works (i.e. has an effect on student misconceptions), why and how does it work? When it does not work, why does it not work?

When students exhibit a change in their thinking from their comments and performance on post-questions, what indications do they give about the explanation, and in particular about the thought situations in the explanation, which would show why and how the explanation was effective? Conversely, when students show little change, what indications do they give as to why the explanation was ineffective? Answers to these questions will provide guidance for further development of explanations and lessons making use of thought situations, and may provide insight into students' interactions with mental models of physical situations.

4) From the students' interactions with the thought situations in each of the explanations, what can be said about students' causal reasoning and use of causal models?

This is a rather open-ended question asking what insights may be gained into students' use of causal reasoning, largely from examination of the protocol data in the interviewing study. Students' causal reasoning, especially that of students beyond elementary school age, has been largely neglected in favor of the exploration of students' acquisition of formal operational thought. Although ability at formal reasoning is undeniably important to success in physics, previous studies by this author have indicated that causal reasoning may be an important area of further research.

Limitations of the Studies

Although the studies touch on a topic which I believe to be of great importance, there are several aspects which may prevent wide generalization of the results. First, the explanations deal with only one content domain - forces from static objects. It could be argued that the results are due to the peculiarities of the particular content domain and the particular explanations, rather than the general principles underlying the construction of the explanations. Second, along the same lines, since the explanations were chosen to be ecologically valid rather than experimentally precise, they differ along more than one dimension. Thus it may be difficult to claim that any observed differences are a result of differences in the explanations along any particular dimension. This difficulty was alleviated by use of the protocol data in the interviewing study and students' written

explanations in the written instrument study, which allowed a closer look at why each of the explanations was or was not effective.

Third, the populations may have been non-representative. This is of particular concern with the subjects for the interviewing study, who came from a high school near a large university, since a larger proportion of students than is typical may have been from households with highly educated parents. This is offset somewhat by the the fact that the written instrument study drew from a different population, but generalizations from the interview data must be made with care.

Finally, the relative effectiveness of the explanations was judged largely by performance on post-questions. If these questions did not test understanding, or if they were biased in favor of one explanation, this would certainly cast doubt on the results. To insure that these difficulties were minimized, the questions were reviewed by subject matter experts and experts on constructing questions to test conceptual understanding. They were also tested on several students prior to the interviewing study to insure that the students interpreted the questions as intended.

CHAPTER IV

INTERVIEWING STUDY

Method

Subjects

For this study, twenty high school students were interviewed who had not yet taken physics, but who came from a population representative of students who might subsequently take physics (in this case, chemistry students). Each of the students received one of two different explanations (these will be described in more detail below). In order to insure that neither the experimental group nor the control group had a higher average intellectual ability, the teachers were asked to rate the students on a binary scale as having a relatively easy or difficult time with conceptual material. Combined with the information about which level chemistry course each student was taking (advanced or standard), each student was assigned to one of four sub-groups. Half of the students in each sub-group were chosen at random to receive one explanation, and the other half received the second explanation.

The Explanations

Control Explanation

Both the control explanation and the experimental explanation consisted of seven short paragraphs. After reading each paragraph aloud, the student was encouraged to express her thoughts, and then further questions were asked to focus the student on the content of the paragraphs and encourage active involvement. The control explanation shown in appendix A contains a verbatim excerpt from a popular and innovative high school textbook[3] which gives a number of examples of Newton's third law. Some of the examples used are a finger pressing on a stone (one of Newton's own examples; the stone presses back on the finger), an athlete running (the ground pushing forward on the athlete is responsible for her motion), and a rifle kick. Added to this verbatim excerpt were two sentences at the beginning and a final paragraph *explicitly* stating that Newton's third law applies to the book on the table situation, and that therefore the table is exerting an upward force. (Note: Because of these additions and the fact that the students reading this explanation had not read the prior material in the text, any failings of this explanation should be viewed as failings of this particular treatment rather than necessarily as a failing of the text itself.)

<u>Experimental Explanation</u>

The experimental explanation arose out of the original tutoring interviews described in the previous studies section of the background chapter and was an attempt to capture some of the instructional strategies of these tutoring interviews. This explanation also makes use of concrete situations from the students' experience, but unlike the control explanation, they form a connected sequence, starting from an "anchor" (a situation for which we know that most students believe there is an upward force, in this case a hand pressing down on a spring), through intermediate situations (e.g. a flexible board between two sawhorses), to the target situation of a book on a table. Thus this explanation shows, by means of this connected sequence of examples, where the force comes from -the microscopic compression or bending of the table.

This explanation is designed to: 1) ground understanding on an anchoring intuition that the student already possesses; 2) help the student develop a conviction that the target problem is in fact analogous to the anchoring case; and 3) build a qualitative, microscopic, causal model of rigid objects (as composed of molecules connected by spring-like bonds) which is also based on the anchoring intuition. By helping the student form an analogical connection from the anchor to the target situation, the experimental explanation helps the student construct a causal model of the table which predicts an upward force. The differences between the two explanations are illustrated in figures 1 and 2. (See appendix A for the actual explanations used.)

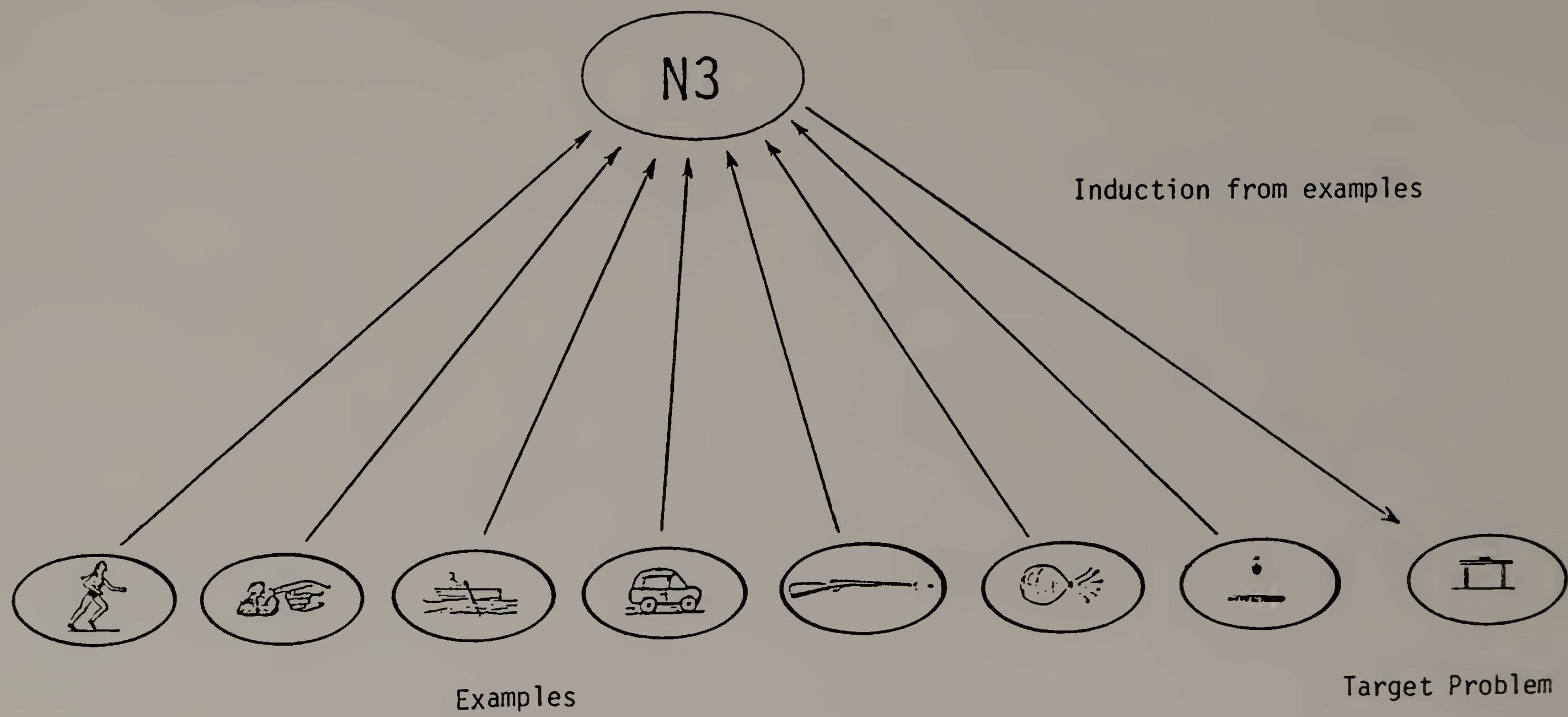


Figure 1

Control Explanation

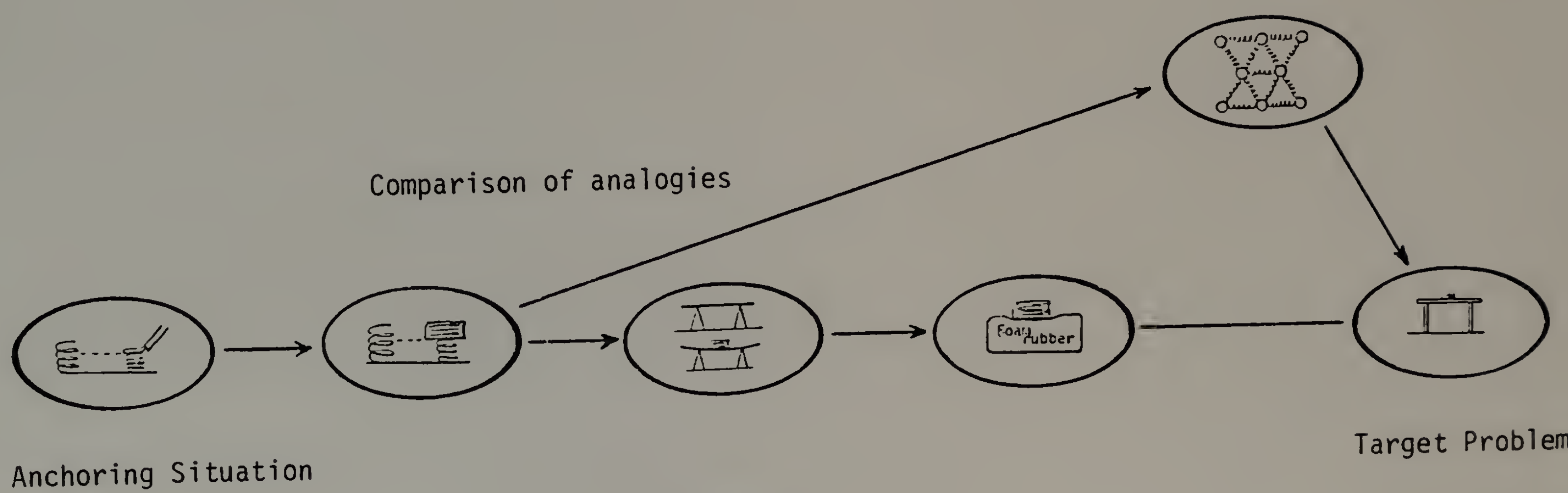


Figure 2

Experimental Explanation

The Pre and Post Questions

Each student received a set of three pre-questions and five post questions (three identical to the pre-questions plus two additional questions - see appendix A for the actual questions used). The purpose of each explanation was to overcome the common misconception that static objects cannot exert forces, thus all the pre and post questions were questions about this general concept. Except for the first question about the book on the table (which asked only about the existence of a force from the table), each question asked both about the existence of a force from a static object, and also whether that force is equal to the force exerted on it.

Each question asked the student to rate her confidence in the answer given, and the interviewer also asked the student to rate how much sense her answer made. Being confident about an answer and an answer making sense were carefully distinguished for the student (see appendix A). The main reason for this distinction is to try to uncover what students intuitively feel is correct rather than what they may confidently know is correct because they happen to remember something in a rote fashion from a television program, a previous science course, or a discussion with a friend taking physics. During the course of reading aloud the written explanation, after each paragraph the student was asked how much sense a particular statement made, along with other probes both to explore his or her reasoning during the explanation and to encourage interaction with the explanation.

Quantitative Analysis

The primary comparisons made between the experimental explanation and the control explanation in the quantitative analysis were between pre-post differences and between performance on transfer problems (which were only asked after the explanations). Also compared were the students' ratings of how much sense each of the examples made in the explanations, as well as the two overall ratings the students gave to the explanations: 1) how understandable and believable the explanation was as a whole, and 2) how much the explanation helped the idea of an upward force from the table make sense. These ratings were obtained right after the student had read the explanation. For the post questions, correct answers on each part of the two part questions were scored as counting one point, and comparisons were made for the scores on each question. The Mann-Whitney test (a non-parametric test similar to a two-tailed t-test) was used for these comparisons.

Qualitative Analysis

Along with the quantitative data provided by the post questions and other numerical scales, the subjects in the interviewing study were videotaped for in-depth study of the interactions with the explanations and the students' explanations of their answers to questions. To further enable analysis of the protocols, each interview was transcribed. In an effort to gain an initial appreciation of student reasoning, two students were chosen as case studies (one student

considered representative from the experimental group and one considered representative from the control group), and their transcripts were examined for instances of causal reasoning and student generated analogies, bridges, and examples.

After this initial look at student interaction with the explanations, the transcripts of the remaining students were also examined for instances of causal reasoning and student generated analogies, bridges, and examples. To investigate the dynamics of student interaction with thought situations, diagrams were drawn showing all of the interviewer and student generated thought situations and all of the comparisons between thought situations. For the text excerpt, the diagrams showed the abstract principle in a circle and the discussions of the thought situations in light of the principle as lines between the thought situations and the principle. (See figures 3 and 4 in the case studies for examples.) Although the protocol analysis was used to provide information relevant to the particular research questions, since this area has been so little explored, much of the analysis was heuristic in nature, providing input to a process of hypothesis formation rather than hypothesis testing.

Case Studies

To begin the analysis of the interviewing data I would like to take a close look at the interactions of two students with the questions and explanations. This will serve two purposes: first, it will acquaint the reader with the way the interviews were conducted, and second, it will

provide a forum for the development of some ideas which will be further explored in later sections. The first case study is of a student who received the control explanation, and the second one is of a student who received the experimental explanation. The numbers along the left hand side of the transcript segments are for reference to the complete transcripts of both interviews contained in appendices B and C.

Control Explanation Case Study

Curt (not his real name) was a standard level chemistry student who was rated by his teacher as having an easy time with conceptual material.

After reading the question about the book resting on the table, Curt responded that the table does not exert a force upward on a book resting on it. He was fairly confident about this answer (a confidence rating of 2) and his answer made quite a bit of sense to him (a sense rating of 4). The table's exerting a force made only a little sense to him (a sense rating of 2).

010 S: Okay, I'd say that it's not exerting an upward force on the
book, because the table isn't pushing upwards towards the
ceiling, there's no movement in the table whatsoever. Granted
you can have, I mean it still has its separate space, but the
book is pushing down the table's not pushing up. If there's no
011 table there, you move the table within 3 feet of the book and
put the book on the same level, and hold it, it'll fall down to
the ground. The table's just acting as a support, not pushing
on the book, not exerting a force upward on the book, as it
says.

Curt apparently viewed the table as an inanimate object which acts simply as a support for the book. In the goat and mosquito problems he further articulated his view that he did not see how inanimate objects could exert forces. The following segment shows his response after reading the first paragraph of the text excerpt in which the answer is given to the book on the table problem.

080 S: I did the first one wrong. And I guess I hadn't thought, I hadn't thought of something that stays still, I guess it stays still, stationary, as exerting a counter-force, other than resistance. And maybe resistance is a force that I am not, fully, ah, set in using. I obviously haven't accrued enough knowledge to ah, answer the first one.
081 I: What, which first one?
082 S: This question relating to the book on the table.

Later, after reading the explanation, Curt indicated he did not believe the table exerts an upward force on the book. As can be seen from the above segment, this is not because he did not realize what the "correct" answer is. Following are some segments in which he indicated his feelings about some of the examples used in the explanation.

098 I: Does it make sense to you that the ground pushes forward on the athlete?
099 S: Um, give me one second and I'll see if it does. ---(15 secs)--- Honestly? Not a whole lot, of sense, I mean, I get a draft of what they're saying, but I can't really understand the logic behind saying that it, the ground, involves a push of the ground forward on her.

114 I: Does it make sense to you that the stone would push back on the finger?
115 S: Um, not a lot of sense. I mean, I could figure, granted, your finger bends and you can feel the stone on your hand. Um, it doesn't make a lot of sense to me that it pushes back. I only see things that don't move, I miss, I have a lot of trouble with this, I have to admit that I only see things that don't
116 move as not exerting a force, a counter force, or an interactive force as they're calling it, but more as a resisting force.

He went on to say that the rowboat example made sense to him because water is more animate than the ground or a stone, a response others gave, but the car example did not make a great deal of sense to him because he viewed the friction responsible for the car's forward movement as simply a resistance rather than a force. He felt the gun and the balloon made sense (as did most), but like others he was confused by the apple exerting an equal and opposite force on the earth. See figure 3 for a diagrammatic representation of Curt's interaction with the control explanation. After reading the entire explanation, he responded to the two questions of whether the explanation was understandable and believable and whether the explanation helped the idea of an upward force from the table make sense.

168 I: Is the explanation on this page, this entire page,
understandable and believable to you?
169 S: Believable, no, because I've always had trouble with anything
with physics. I'm more of a literature, literary-type person.
Where, you can talk about it, and science is great, but it has
its own place somewhere else. Um, I'm not really much a fan of
physics, and I tend to stay away from it as much as I can. I
170 mean I read a little bit on it. But, understandable, yes, I
understand it. I understand how it can happen, why it happens.
But, believable, I just find that, you know, how can, I don't
see the logical arguments that, that the ground is actually
making a force propelling the girl forward while she steps back.
171 Um, so far, they've just told me stuff, they've given me
examples of how it happens, and why it happens. But, um, those
aren't really sufficient, without knowing any of the formulas of
how it comes about, or if there is actually this force, or it's
just a theory.
172 I: Okay.
173 S: Maybe I'm doubting one of the biggest philosophers of all time,
Newton, but he has been wrong before about the counter force,
the force inside a vacuum, that says two things don't fall at
the same rate. The New York Times published an article about
that. So, to say that this is exactly right and exactly

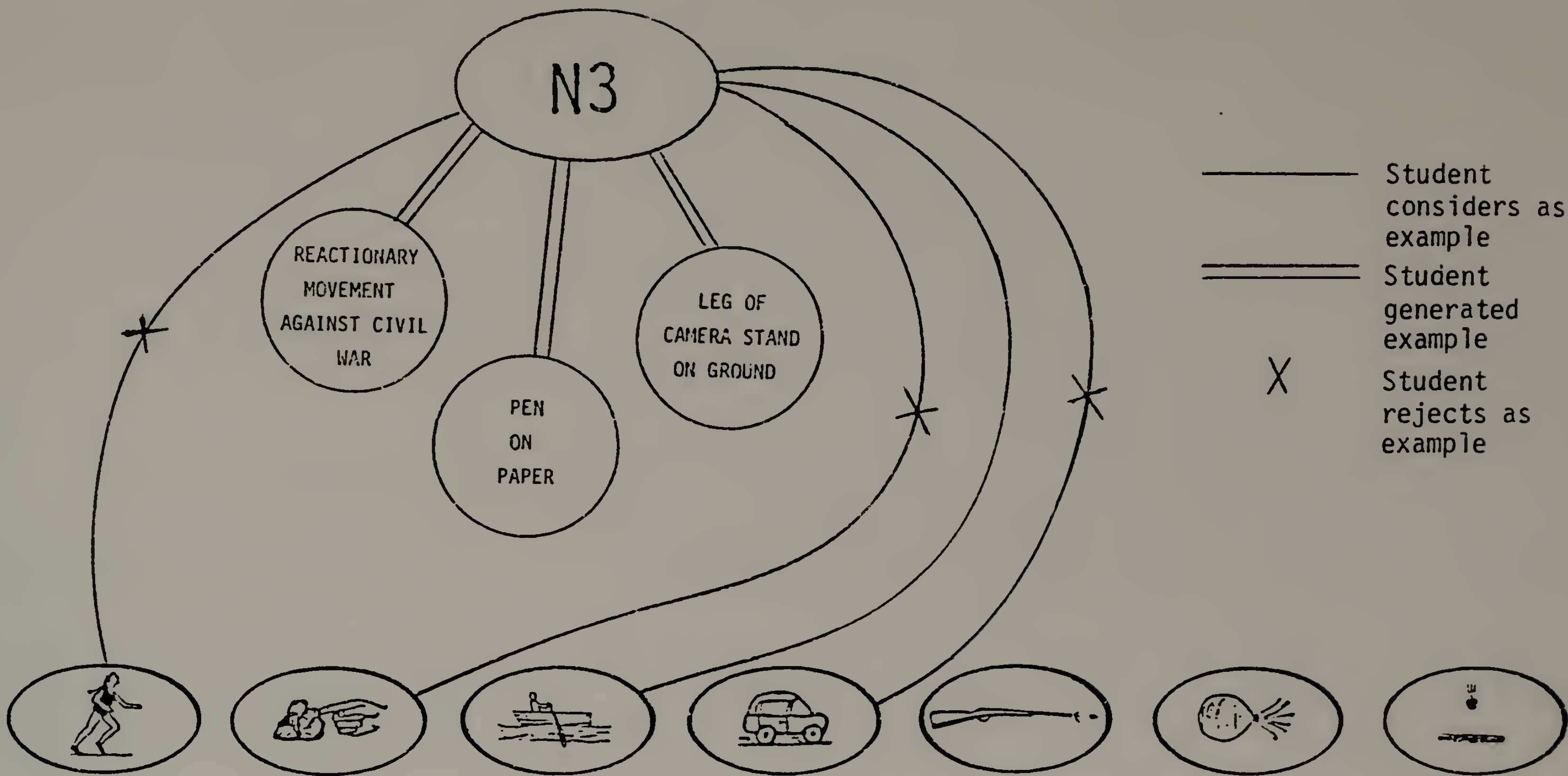


Figure 3

Control Case Study Diagram

174 correct, stands to reason, ah, more or less, you know, give or
take situations. Maybe it's exactly correct or maybe it's
exactly wrong. I understand it but it's not at all wholly
believable.

175 I: Okay, and let me ask, um, does the explanation on this page help
the idea of an upward force from the table, make sense?
176 S: No, no it does not.
177 I: And let me, here's another scale if you could just rate how much
um, the explanation helps, the idea of a force to make sense, on
that scale from one to five.
178 S: Okay, it helps a good amount to make sense. It helps me to
understand, you know, how it happens, the actual, the actual
actions that make it happen, the step down on the ground, the
rowing of the oars, the shooting of the bullet. It helped me
to, that made sense in my mind how that happens. But it, on
179 the same turn I'd have to put it down lower because I don't
fully believe all the stuff that it's saying. I don't believe
that those are the principles that make the car go, that that is
why the rock is pushing exactly the same amount back on the
finger.

It is interesting to note that apparently what Curt felt made sense in the explanation was what could be called the "action" in each example. However, the "reactions" made less sense because he did not believe that inanimate objects could exert forces. He had been given no way of thinking about the "reactors" which would make them feasible sources of force in his mind. As a result he rejected the conclusion of the explanation and continued to maintain that a table cannot exert a force on a book resting on it.

204 S: "A book is at rest on a table. Which of the following do you
think is true?" The only thing is if I answer this, I know,
said that Newton's Law says that it does. But, okay they want
what I think. I still think that it doesn't. And I'm pretty
confident about that. And why I don't think it does is because
205 I haven't been given enough evidence to prove that it actually
does. I mean, I can only handle so much physics-type things.
You know, gravity is about the extent of my physics mind. And
to say that there's forces beyond thinking, beyond, you know any
control of the human being, um, pushing up on a book, or even
206 the book pushing down on the desk, are odd. The only reason I

> know that the book is pushing down on the desk is because gravity is a real force, it's a magnetic force. You know out in space where it's out, right outside of the magnet, the book would stay right in mid-space and would not fall. That's why.

He continued to maintain also that the wall does not exert a force back on the goat and that the monument does not exert a force on the mosquito. However, when he came to the two boxes problem, he maintained that stating the problem in terms of weight was helpful for him. "Weight seems to be one of the few things that I can, that I understand. And using actual numbers...puts me on a little firmer ground."

When asked about the relative size of the forces, he initially stated that the ground would exert the larger force (the correct answer), then he changed to equal force and then back again to the ground exerting a larger force. His reasoning for the ground exerting the larger force seemed to be that the ground covers a larger area on the bottom of the lower box than the 50 pound box does on the top of the lower box.

261 S: Because there's more area on the bottom of this box. There's more force pushed up on it. This bottom, the little base is faced right here. More force is being pushed on it, as in, not as much force is being pushed on these little separate sections of this box by this 50 smaller box. Um, that's why I said 'yes,' see how sure I was.

However, as can be seen below, this understanding is less than adequate. Even though the explanation spent a significant amount of time developing the idea of force as an interaction between two objects, apparently Curt continued to view force as a property of an object (the more weight an object has the more force it has) rather than as an

interaction. Even though the explanation stated numerous times that the forces would be equal in such an interaction, Curt did not mention this at all in this problem.

275 S: "A large steel block weighing 2, ah, two hundred pounds rests
on a small steel block weighing 40 lbs. as shown below. Think
about whether A exerts force on B, and whether B exerts a force
on A." And I have to say 'yes,' because weights are starting to
make me feel more comfortable. This, so I'd have to say I'm
276 more towards 'fairly confident.' And I'm getting a better
understanding using the numbers, using weights makes me feel
more sure about myself, ah, for some unknown reason. Maybe
it's, maybe it's just because they're strewn out in front of me.
But, um, so I'm more, I'm fairly confident that this box is
277 putting up a resisting force to A which is more on top. If I
said 'yes,' A and B, A exerts a larger force. That was, there.
I would say that A and B exert a force on each other, but A
exerts a larger force, more weight, and covers the entire face
of this box, with 200 lbs. of pressure which is 160 more lbs.
pushing down on the box. And I'm more or less confident about
that.

Thus it appears that the explanation had little effect on Curt's belief that inanimate objects can exert forces. When he did begin to believe this toward the end of the post questions, his reasoning was based on an inadequate understanding of force as a property of an object rather than as an interaction between two objects.

Experimental Explanation Case Study

By way of contrast, the following subject's beliefs were apparently changed by interaction with the experimental explanation. John (also not his real name) was an advanced level chemistry student who was rated by his teacher as having a difficult time with conceptual material. See appendix C for a complete transcript.

When John initially answered the book on the table problem, he indicated that the table would not exert an upward force on the book, that he was fairly confident about this answer (a confidence rating of 2), and that this answer made perfect sense to him (a sense rating of 5). The table's exerting a force made no sense to him (a sense rating of 1). When asked to say why he answered the way he did, he indicated that although it was difficult to articulate the reason for such a deep-seated belief, his concept of gravity as well as personal experience played a part.

013 S: "Please explain why you think the table exerts or does not exert
a force up on the book." Hmm. I, can't explain it, it's common
sense I guess, cause my hand's above the book, above the table
right now and it's not exerting any force. Do you know what I
mean? I mean it's hard to explain why, but I, my hand's on the
014 table right now and it's not exerting any force upward on my
hand.
015 I: The table?
016 S: Yeah.
017 I: Uh huh.
018 S: You know, I guess gravity would be good.
019 I: Gravity?
020 S: Well, I don't know, it's hard, please explain why I think.
Experience I guess. It's hard to explain why, do you know what
I mean? Because I've had things on tables for my whole life,
and it's never exerted force upward

When answering the goat problem, John said "I thought for a second that I remembered somewhere in my science years that the wall would exert a force back, but I forget when." As a consequence his confidence rating for his answer (which was that the wall would not exert a force) was "not very confident." However, as with the table problem, it made perfect sense to him that the wall would not exert a force and it made no sense to him that it would. For the mosquito problem he again

answered that the monument would not exert a force, and this answer also made perfect sense to him. On this problem he moved his confidence back up to fairly confident.

The following excerpt shows his reaction to the first paragraph of the experimental explanation. He said spontaneously that he did not see what pushing down on a spring has to do with a book on a table (a clear indication that he saw no analogy relation). When asked how the table and the spring are different, he indicated that with a spring there is pressure from the spring to push your hand up to a higher level whereas with a table there is no such pressure.

085 S: "In this exercise we will consider the question of whether a table pushes up on a book resting on it. Consider pushing down on a spring with your hand."
086 I: What are you thinking?
087 S: I don't see what pushing down on a spring with your hand has to do with putting a book on the table.
088 I: Does it make sense to you that the spring would push up on your hand?
089 S: Oh yeah. It would put pressure on your hand.
090 I: OK. How much sense does it make that the spring would push up on your hand?
091 S: Makes perfect sense.
092 I: OK. Umm, is this different from the book on the table?
093 S: The spring on the hand?
094 I: Yeah.
095 S: Yeah, I think so.
096 I: How so?
097 S: Because the table isn't forcing your hand up, and you don't have to put any pressure on the table so your hand doesn't come back up. With the spring you have to put some pressure on the spring so it doesn't push your hand up. Do you know what I mean?
098 I: I'm not quite sure I...
099 S: Well, you're talking about pressing down on the spring, right?
100 I: Right.
101 S: If you press down on the spring there's some pressure from the spring to push your hand back up.
102 I: Uh huh
103 S: Put your hand on the table there's no pressure whatsoever pushing your hand back up

After reading the second paragraph, he said an upward force on the book on the spring made perfect sense for the same reason that the hand on the spring made perfect sense, an indication that he saw an analogy relation between these two situations of the book and the hand on the spring. This is an important point, because although this analogy relation may seem patently obvious to a scientifically trained person, in past tutoring interviews several students have needed help in developing this analogy relation, believing a spring would push up on a hand but not on a book.

After reading the third paragraph, he said with no explanation that the book on the spring was different from the book on the table. However, as the following excerpt shows, after reading the fourth paragraph in which the intermediate situation is presented of the flexible board between two sawhorses, he seemed to become more engaged with the explanation and indicated that the idea of an upward force from the table began to make some sense. When asked whether the book on the board situation is different from the book on the table, he sounded much less confident than earlier in answering that the situations were different. At the end of the excerpt, he seemed to indicate that thinking about the continuous transformation of increasing the thickness of the board was having an effect on his conception of a force from the table.

131 S: Starting to make some sense...can't imagine this bending any for a book, to press back on it. [presses desk with hand]
132 I: Does it make sense to you that the flexible board pushes up on the book?
133 S: Pushes up on it?

134 I: Yeah.
135 S: Yeah...
136 I: How much sense?
137 S: Makes perfect sense.
138 I: What would happen if the board got thicker and thicker?
139 S: Umm, it would bend less and less..guess the pressure would become less and less too.
140 I: Is the book on the board situation different from the book on the table?
141 S: Ummm, I guess so, I mean, amount of pressure.......do you want me to keep reading?
142 I: What are you thinking?
143 S: I'm thinking it's starting to make some sense.
144 I: How so?
145 S: Well, that the flexible board bends, and if you just, if there, the board's gonna bend less and less, I guess there'd be some pressure back..

As the following excerpt shows, the intermediate situation of the foam rubber also seemed to help.

149 S: Starting to understand a little bit...
150 I: Does it make sense to you that the foam rubber pushes up on the book?
151 S: Foam rubber pushes up on the book. Yeah, makes sense, horse sense. Isn't that foam rubber, that's not styrofoam, we're not thinking about styrofoam, we're thinking about rubber, foam rubber
152 I: Yeah
153 S: That makes sense. Makes perfect sense
154 I: Makes perfect sense. Is the book on the stiff foam rubber situation different from the book on the table?.....
155 S: Umm...uhhh, no I guess not
156 I: What are you thinking?
157 S: I was just thinking about the different materials
158 I: Different materials?
159 S: Of the rubber and the table. I guess it would make a difference
160 I: What were you thinking about them?
161 S: Well, it would be a difference in the pressure exerted back, but...

After reading the final two paragraphs, he said it "makes sense the way this is explained." He said that the explanation was very understandable and believable (shying away from a perfect rating because

"I don't think anything's completely believable") and that it helped a good amount to make sense of the idea of an upward force from the table. See figure 4 for a diagrammatic representation of John's interaction with the experimental explanation.

In the following excerpt, John was asked which examples helped the idea of an upward force from the table make sense and which did not help. He began to indicate that he believed the spring analogy did not help, but then he realized that a "way has been built up" from the spring to the table by means of intermediate analogies. He thus indicated that he was aware of how the bridging strategy helped him make sense of the book on the table situation, even though this strategy was never described to him.

190 I: Which examples on this page helped the idea of an upward force from the table make sense and which did not help?..
191 S: I don't think the spr.., well, I guess I didn't think the spring helped, but in context I guess..out of context you just compare the spring and the table it wouldn't help, but you sort of built a way up from the spring, which is obvious, to a flexible board, to a not so flexible board, to foam rubber, to a table, which is pretty good. So I wouldn't think there's anything in here...
192 I: Were there any examples that didn't help?
193 S: No, I don't think so.

On the post book on the table question, John answered that he now believed the table exerts an upward force, and his confidence was between fairly confident and completely sure (a rating of 2.5). When asked to explain his reasoning, he referred to the molecular model, an indication that this model was important in his thinking about the table.

221 S: That the molecules compress when, um, pressure's put on 'em, and they exert the same amount of pressure back on, or the same weight, back on whatever's putting pressure on 'em. And when the pressure is relieved, the molecules decompress.

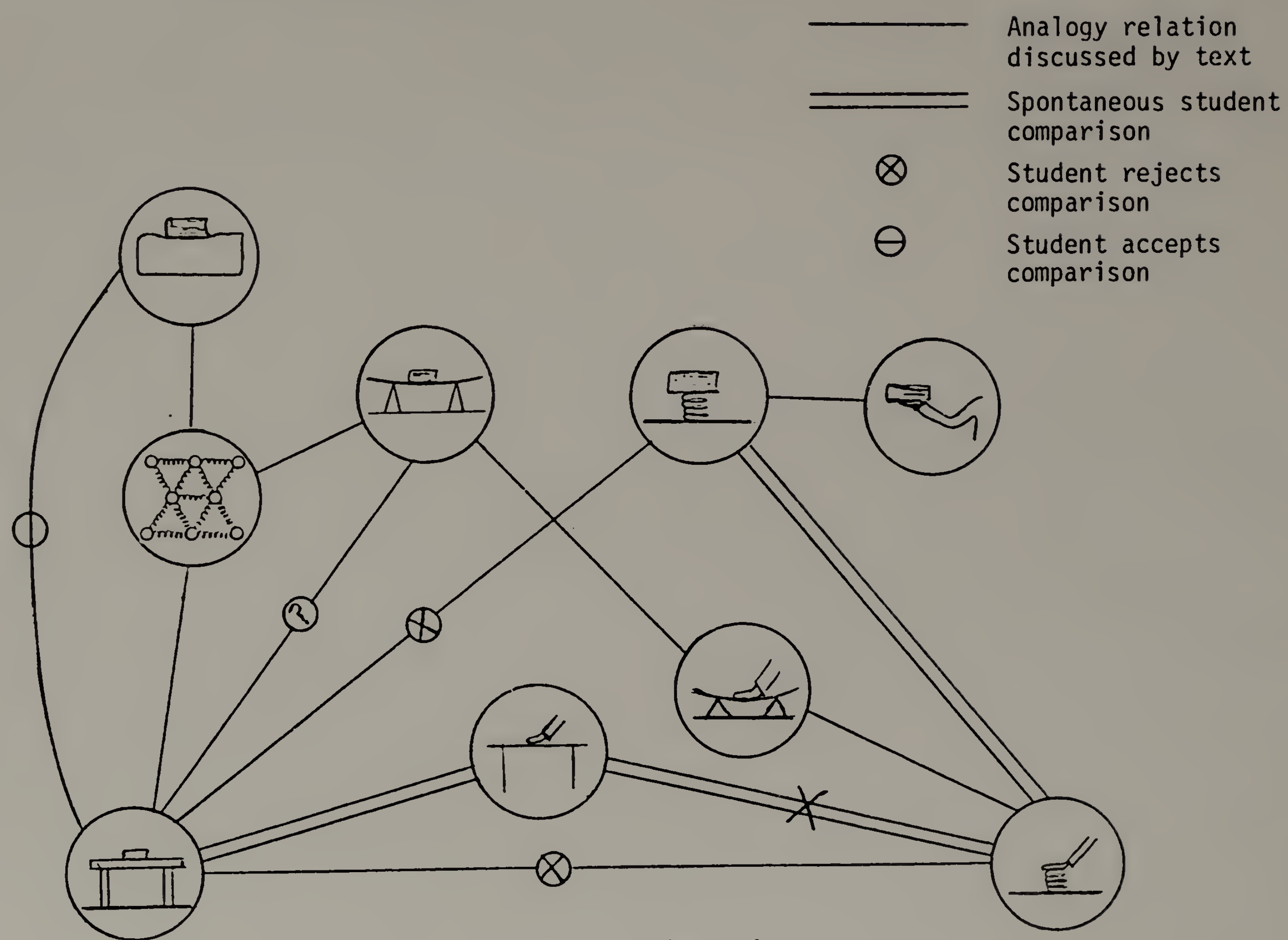


Figure 4

Experimental Case Study Diagram

222 I: Ok. And how much sense, um, get the sense scale again, how much sense does it make that the table exerts a force upward on the book?
223 S: Makes quite a bit of sense, four.
224 I: And how much sense does it make that the table does not exert a force upward on the book...
225 S: Umm...., makes some sense..
226 I: So a three
227 S: Yeah

On the post goat problem, John answered that the wall exerts a force back on the goat with a confidence of 2.4. Initially his sense rating was a four, but upon reflection, he changed that to a five because of an indirect causal argument.

237 S: Actually it makes a lot of sense, cause if, cause if it exerted more it would cush, push the goat back, and if it exerted less, it would break..That's right isn't it?
238 I: Well, I won't say.
239 S: Well, yeah, that's the way I think about it a little bit.
240 I: So are you, so how much, what rating would you give it?
241 S: Makes, makes, wellll, yeah, I guess it makes perfect sense to me.
242 I: Ok. And could you explain in your own words, um, why you answered the way you did?
243 S: Because if it exerted less it would break, and if it exerted more it would push the goat back.
244 I: Ok. And why did you answer that the wall was exerting a force?
245 S: Because of the thing I read.
246 I: Ok, how would you, how would you explain it in your own words?
247 S: Because the molecules compress, and, um exert the same amount of pressure back on the goat as the goat is making on the wall.

In the following excerpt John seemed to still be struggling somewhat with the idea of objects being springy which seem rigid. John answered the mosquito problem correctly and said that it made perfect sense to him that the monument would be exerting a force upward on the mosquito. But when asked for any other comments he responded as

follows, indicating that his answer made sense only because of the explanation, and apparently only because of the molecular model.

261 S: It's hard to imagine a mosquito making any kind of, um, force on the monument which is, uh, pretty hard. Doesn't make much sense. Well it makes a lot of sense, I mean now that it was explained to me. It doesn't make a lot of common sense. Do you know what I mean?
262 I: How are, how are you distinguishing that?
263 S: Well because, from this [the explanation], I understand that when something, when some pressure's put on something, it compresses, even the littlest amount, and pressure's exerted back. But it's hard to see a mosquito making a little dent, molecular dent. Yeah, a little indent in the monument, just because it landed on it.

Following is John's explanation about his answer to the two boxes problem, a non-example in that the forces to be compared are not equal. Like Curt, he got this problem correct. However, unlike Curt, he focused on the compression of the ground as providing the upward force rather than focusing on the irrelevant feature of the amount of surface area in determining the forces. The molecular model seemed again to be important in his thinking.

278 S: Um, the ground, the ground exerts an upward force because a hundred, actually 150 pounds worth of pressure is on the ground and compressing the molecules. The molecules are exerting 150 pounds worth of force back. And the ground exerts the larger force cause it's exerting 150 pounds worth of pressure whereas,
279 um, whereas the higher box is only putting 50 pounds of pressure on the lower box.

On the final problem, John answered both parts correctly, but on the part asking about the relative sizes of the forces, he seemed to indicate that he was torn between viewing the force from B as arising from the compression of its molecules (indicating an interaction view of

force) and B's weight (indicating a view of force as a property of objects). Although he chose correctly the view of force as an interaction, it seems clear from the following excerpt that he was still strongly drawn toward the concept of force as a property. Although he seemed to have made significant progress, this indicates that it is perhaps too optimistic to expect a complete overhaul of his conception of force as a result of this limited intervention.

283 S: Well B exerts..200 pounds worth of upward pressure on, uh, A, cause the molecules compress, actually, well actually that really doesn't make that much sense to me, but I'm putting it down because of this here.
284 I: Of the explanation?
285 S: Yeah. I don't understand how something that weighs 40 pounds can exert 200 pounds worth of pressure....
286 I: Ok, so..
287 S: A and B exert a force on each other but A exerts a larger force. I'm fairly confident about that cause, uh, A weighs more..
288 I: Ok.
289 S: Well, I don't know if I'd say that. I might as well be consistent. Cause that exerts 200 pounds worth of weight down on B, that puts 200 pounds back up.
290 I: Could you explain why you changed the way you're thinking?
291 S: Well, I changed because I might as well be consistent..with this
292 I: With the explanation?
293 S: Uh huh, because it would put the same amount of pressure back up on it that's being put down on it.

----

298 I: Ok. Um...before you said something that it didn't makes sense to you that something which weighed 40 pounds could exert 200 pounds
299 S: Worth of pressure?
300 I: Yeah. What were you thinking there?
301 S: I don't know. I, just that, it doesn't make sense that 40 pounds could exert 200 pounds worth of pressure
302 I: Uh huh.
303 S: Yeah.
304 I: Could you say why?
305 S: Cause it weighs 40 pounds
306 I: Uh huh
307 S: Yeah. Well, B if it weighs 40 pounds.
308 I: Ok.
309 S: And I know that's not true, I know it can, but it just doesn't make sense to me.

John's answer choices and confidence and sense ratings as well as the protocol segments above provide an initial indication that the experimental explanation was effective in bringing John to a new view about forces from static objects. There appear to be three reasons for the effectiveness of the explanation: 1) the examples made perfect sense to John, 2) a way was "built up" from the conceptual anchor to the target problem by developing the analogy relation using bridging analogies, and 3) the molecular model seemed to be important to John as he used it in reasoning about all of the post questions.

It also appears that some progress was made in changing John's conception of force from that of force as a property of objects to that of force as an interaction between objects. However, it is interesting to note that even though some progress was made, John still expressed some reservations about the monument's ability to exert a force on the mosquito and about the idea that the forces would be equal in the steel blocks problem. Thus, although the experimental explanation seemed to have had some effect, it is perhaps overly optimistic to expect deep-seated beliefs to be changed with such a limited intervention.

Conclusions

From the protocol data of these two case studies, the experimental explanation appears to have had an impact on John's belief's about forces from static objects as well as his general concept of force. By contrast, the control explanation appears to have left both untouched.

Curt, who received the control explanation, seemed to have based his reasoning in the final two problems, in which he did indicate a force from static objects, not on the conclusion of the explanation but on the statements of the problems in terms of weight, indicating a conception of force as a property of an object. In the following two sections, first numerical data from other students are examined, and then some possible reasons for the differences in student performance are explored.

Quantitative Results

Of the fourteen students initially maintaining that there is no force from the table, seven received the control explanation and seven received the experimental explanation. To the "Book on the Table" post-question, all seven receiving the experimental explanation expressed a confident belief in an upward force from the table. However, of the seven receiving the control explanation, five answered the table problem incorrectly after reading the explanation, even though the explanation had explicitly stated the correct answer to this problem. There were also significant differences in performance on the other post-questions in favor of the experimental explanation. Brief descriptions of the five problems follow.

Question 1 asked only about the existence of a force from the table. Questions 2 through 5 asked both about the existence and the relative magnitudes (or equality) of the forces between other static objects. Question 4 concerns a non-example in that the forces to be

compared are not equal. Following are some tables of results for the fourteen students initially indicating that the table does not exert an upward force. Seven of these received the control explanation, and seven received the experimental explanation.

In tables 1 and 2 the first three columns indicate the number of students answering correctly for each part of each problem before reading the explanation. The first two columns show the number of students answering correctly about whether there is a force from the static object, and whether the forces to be compared are equal or not. The overall score indicates the total number of correct answers for each problem. The next three columns contain the same quantities for the questions asked after the students had read the explanations. The last column indicates the pre-post differences between the pre and post overall scores.

Table 3 then compares these overall pre-post differences. (Note: Since questions 4 and 5 were asked only after the explanation, they do not have pre-explanation scores and table 3 compares the overall post scores.) In addition, table 3 presents a comparison of students' ratings in response to two questions asked after the explanation: 1) was the explanation understandable and believable, and 2) did the explanation help the idea of an upward force from the table make sense. For both of these questions, a 5 indicates the best possible rating.

These results indicate that the students responded differently to the two explanations. All of the students initially answering the table problem incorrectly and who received the experimental explanation answered the post question about the book on the table correctly and

Table 1

Number of Students Answering Correctly:
Control Explanation
(Students Initially Answering Table Problem Incorrectly)

	Pre-questions			Post-questions			Overall
	Exist.	Equal.	Overall	Exist.	Equal.	Overall	pre-post
1) TABLE	0	-	0	2	-	2	2
2) GOAT	2	1	3	4	2	6	3
3) MOSQUITO	1	0	1	2	2	4	3
4) TWO BOXES	-	-	-	4	1	5	
5) STEEL BLOCKS	-	-	-	3	0	3	

Table 2

Number of Students Answering Correctly:
Experimental Explanation
(Students Initially Answering Table Problem Incorrectly)

	Pre-questions			Post-questions			Overall
	Exist.	Equal.	Overall	Exist.	Equal.	Overall	pre-post
1) TABLE	0	-	0	7	-	7	7
2) GOAT	3	2	5	7	6	13	8
3) MOSQUITO	1	1	2	7	7	14	12
4) TWO BOXES	-	-	-	7	6	13	
5) STEEL BLOCKS	-	-	-	7	6	13	

Table 3

Comparison of Overall Performance
(Students Initially Answering Table Problem Incorrectly)

	Control	Experimental
Pre-post differences		
1) TABLE	2	7 **
2) GOAT	3	8
3) MOSQUITO	3	12 **
Post scores		
4) TWO BOXES	5	13 *
5) STEEL BLOCKS	3	13 **
Student ratings of explanations		
Understandable and believable?	3.4	4.7 **
Helps to make sense?	2.9	4.7 **

$P < .05$ Difference in favor of the experimental group
** $P < .01$

with high confidence (average confidence score of 2.8 out of 3). They also indicated that this answer made a great deal of sense to them (average sense rating of 4.6 out of 5), and their performance on other post questions was quite encouraging. Particularly encouraging is the fact that six of the seven students answered both parts of the steel blocks problem correctly, a difficult transfer problem which draws out the strong intuition in many students that force is a property of objects. Many thus answer that block A exerts the larger force since it is heavier. On a recent high school diagnostic test, after a full year of traditional instruction in physics, from a sample of 50 students only 24 answered this problem correctly (unpublished data).

By contrast, of the seven students who initially answered the table problem incorrectly and who received the control explanation, five answered the table problem incorrectly after reading the explanation, continuing to maintain that the table does not exert an upward force on a book resting on it. Their performance on other post questions was equally discouraging. In particular, none of them answered both parts of the steel blocks problem correctly. Several possible reasons are explored in the following section for the observed differences in student reaction to the two explanations.

Descriptive Observations and Discussion

The case studies and the quantitative results both provided indications that the experimental explanation was more effective than the control explanation in changing students' beliefs about forces from

static objects and in changing students' concept of force to that of force as an interaction between objects rather than as a property of objects. In this section, further evidence is provided of the superior effectiveness of the experimental explanation, and several possible reasons are explored for these differences.

Induction Less Effective Than Bridging

Book on Table Post Question

Control group. As the above results indicate, despite the fact that the control explanation stated a principle which was supported by a number of examples from the students' experience, and also that the explanation explicitly stated that the book on the table was another example of the stated principle, the majority of the students continued to maintain the absence of a force from the table. There are at least two possible reasons for this failure: 1) the students did not realize that the principle explicated in the control explanation (Newton's third law) should apply to the book on the table situation, or 2) they realized the principle should apply, but they simply refused to accept this conclusion. Because the explanation explicitly stated that the book on the table was an example of Newton's third law, it is difficult to accept the first reason. Students' statements do in fact provide support for the second reason.

Following are tables 4 and 5 showing individual numerical student response to the post table problem. A plus (+) indicates that the

student answered the problem correctly and a minus (-) that he answered it incorrectly. Following these tables are some short segments showing each student's reasons for acceptance or rejection of the conclusion of the control explanation. In these tables and transcript segments, individual students are differentiated as, for example, student from the experimental group number 4 (SE4).

SC1 was one of the two students who changed and accepted the conclusion that the table would exert an upward force. However, even though he answered the question correctly, he still maintained that the table's effect on the book should not be called a "force," but rather a "resistance." It is interesting to note that the reason he gave was an indirect causal argument (i.e. if the table were not there, the book would move down) apparently based on a model of an active force pressing against a barrier or resisting object. To the question "is the table exerting a force or is it just in the way?" it is likely that he would have answered the latter.

SC1: Well, if, well considering that everything before is true, um, I'd say that I would have to agree now that the table exerts a force up on the book, but again I wouldn't use the word force, I'd say a resist, a resistance.

SC1: Ok....It's pretty bad to put I'm sure I'm right one way and then I'm sure I'm right the other way, but....I think it exerts a force up because if it didn't exert a force at all, or less of a force than the book, then the book wouldn't be there.

SC2 indicated that he took the idea of action and reaction into account when initially answering the problem, but even after reading the explanation, he still maintained that there is only one force acting in

Table 4

Responses to the Post Table Problem:
Students Who Received the Control Explanation

Student	Table Problem	Confidence	Sense (force)	Sense (no force)
SC1	+	3.0	4	1
SC2	-	2.3	4	4.5
SC3	-	2.1	2	4.5
SC4	-	2.0	2	5
SC5	-	1.0	2	4
SC6	+	2.0	4	4
Curt	-	2.0	3	4

Table 5

Responses to the Post Table Problem:
Students Who Received the Experimental Explanation

Student	Table Problem	Confidence	Sense (force)	Sense (no force)
SE1	+	2.0	4	3
SE2	+	3.0	5	1
SE3	+	3.0	4.5	1
SE4	+	3.0	5	1
SE5	+	3.0	5	1
SE6	+	3.0	5	3
John	+	2.5	4	3

the situation of the book on the table, the book's weight pushing downward.

SC2: Alright, I still say the table does not exert an upward force on the book because I did take the third law into account when I was first doing this, and, um, it still seems to me that the book is essentially being the down, being the, um, object pushing downward. However, since the, did um, put me in the frame of mind to consider the secon, the third law, I would have to move the confidence rating down slightly more to fairly confident.

For SC3, the lack of the table's ability to "force itself upward" was one of the contributing factors to her rejection of the conclusion. It appears that the idea that gravity can only act downward also played a part.

SC3: Ok, well, I still kind of think that, um, the table can't really force itself upward or else it would have to leave the ground to be able to make a force up, and the book, um, has the gravity pulling it down. Both things, actually, gravity pulls the table down and the book down, and that's why I think that it doesn't exert a force up on the book.

SC4 put an interesting twist on the indirect causal argument by indicating that if the table were not there, the book would fall, but if the book were not there, the table would not fly up into the air. This indicates a pitfall of an indirect argument based on a model of two active sources of force pressing against each other when applied to the situation of forces from static objects.

SC4: And why? Because, um, if we were to remove the table from underneath the book then the book would fall, but if we take the book off the table, the table isn't going to start rising. So, um,..so that makes me think that it's ridiculous to think that the table's exerting any force, but they just had a whole page trying to explain to me that it does, so that makes me less confident.

SC5 also indicated that he saw only the downward force of gravity acting in this situation.

SC5: I still don't see the table exerting an upward force on the book, and I'd have to say not very confident just because of um, all the, the examples and evidence and what not that I've read to the contrary, but I'd just, it didn't really sway me that much, but it just made me a little bit less sure of my own answer. And um, I think that the table doesn't exert a force upward on the book basically because of gravity and both objects seem to be exerting a downward force towards the earth because of gravity so I don't see an upward force existing.

SC6 was the other of the two students who changed and answered the table problem correctly after reading the control explanation. She seemed to answer based on a paraphrase of Newton's third law, and she gave an analogy (throwing the pen on the ground) to support her answer. Although she answered the problem correctly, when she was asked whether the explanation helped the idea of an upward force from the table make sense, she responded that it did not help and gave it a rating of 2 out of a possible 5 concerning how much it helped.

SC6: Why? "Why do you think the table exerts or does not exert a force up on the book?" Um, because after reading that it said that whatever you put, whatever you put something on it's going to, like an action reaction, it's going to give you, yeah, you put something on another, obviously it's holding it up. Now if you threw it down the ground, what's holding it up, if you threw the pen on the ground, the ground is giving it a reaction.

Although Curt's answer is discussed in more depth in the case study, I include it here for completeness.

204 S: The only thing is if I answer this, I know, said that Newton's Law says that it does. But, okay they want what I think. I still think that it doesn't. And I'm pretty confident about that. And

> why I don't think it does is because I haven't been given enough evidence to prove that it actually does. I mean, I can only handle so much physics-type things. You know, gravity is about the extent of my physics mind. And to say that there's forces beyond thinking, beyond, you know any control of the human being, um, pushing up on a book, or even the book pushing down on the desk, are odd.

All of the above students explicitly stated in their reasons for their answer that the control explanation indicated that the table exerts an upward force (SC3 indicated this in a later section of the transcript). Thus, all of the students were aware of what the "correct" answer should be according to the explanation, but still five of the seven refused to accept this conclusion. Of the two who accepted the conclusion of the explanation, one (SC1) indicated that he believed "resistance" to be a better word than "force" to describe the effect of the table on the book, and the other (SC6) indicated that she saw the explanation as helping "only a little" to make the idea of an upward force from the table make sense. There is thus strikingly little evidence that the control explanation was at all helpful in improving these students' conceptions of the ability of static objects to exert forces.

Experimental group. By way of contrast, all seven of the students who received the bridging explanation and who initially answered the table problem incorrectly changed and answered the post question correctly about the book on the table. Following are short transcript segments showing why each of these students gave the correct answer.

SE1 indicated that the springy or flexible board analogy helped him comprehend the answer.

SE1: That seems right, and I'm fairly confident cause, cause it's just like the springy board and the table.

SE2 gave a reason which was initially indirect causal (the book presses on the table so the table must exert a force back to relieve the stress), but then he mentioned that the table must readjust and indicated that the molecules of the table are springy, thus providing an agent (springiness) which is responsible for the force.

SE2: The reason that I'm sure I'm right is that I know that the book is applying stress upon the table and it is applying force upon the table and hence the table must exert the same amount of force back onto the book to relieve its stress and readjust. And I also know that the molecules of the table are springy and flex.

SE3 gave a purely indirect causal argument, indicating both that the table would collapse and the book would fall down if the table were not exerting force.

SE3: Well, there has to be exerting an upward force from the table because if it didn't, it would collapse, and also it, it, it's just the, the balance. If it wasn't exerting any, the table, the book is exerting some force going down, and if there was no resistance to it, it could just, it would just go straight down.

SE4 also answered using an indirect causal argument, indicating again that either the table would break or the book would be on the floor if the table did not exert an upward force.

SE4: Because if it was not exerting a force upward on the book the book would move through the table and break the table or it would be on the floor. It's exerting a force equal to whatever, upward equal to whatever force the book is putting on it to move down.

SE5 referred to the table in a somewhat anthropomorphic sense as trying to get back to its regular shape. Thus he gave a direct causal argument for the table exerting a force by attributing volition to the springy table.

SE5: Having the uh, book forces uh, puts a uh, force equal to the, er, or a force down on the table and the uh, and the table being want to resemble its same shape pushes a force back on the book also to equalize the force to force relationship, and uh, try to get back to its regular shape.

SE6 was the one student who said he thought the hand on the spring situation was not essentially different from the book on the table after reading the first paragraph of the experimental explanation. He said that the spring "just measures the amount of pressure more evidently." In this answer to the post book-on-the-table question he began to talk about the springiness of the table and then apparently felt that that might be unnecessary, perhaps since he became convinced early on that the table and spring situations were equivalent.

SE6: I think it exerts a force cause the table has an inherent springiness which, well, I don't know if I want to talk about the springiness, it's, well, why do I think it exerts a force. It's because, because the book exerts a force down, the table likewise exerts a force up.

John's answer is discussed in more detail in the case study, but it is included here for completeness.

221 S: The molecules compress when, um, pressure's put on 'em, and they exert the same amount of pressure back on, or the same weight, back on whatever's putting pressure on 'em. And when the pressure is relieved, the molecules decompress.

These responses indicate that the experimental explanation had an effect on the students' conscious conceptions about forces from static objects. Four of the students gave a direct causal explanation indicating the agency responsible for the force, two gave an indirect causal argument indicating that a force must exist, and one gave both types of argument as a reason for why the table exerts an upward force.

Two Boxes Problem

Included in the post questions were two which the students had not encountered before reading the explanations, both of which were fairly difficult transfer problems. The first one (the two boxes problem, see appendix A) is a non-example in that the forces to be compared (the force exerted by a 50 pound box on top of a 100 pound box compared with the force the ground exerts on the 100 pound box) are not equal. The second one was the steel blocks problem about a 200 pound block on top of a 40 pound block. This is a difficult problem in that most students find it hard to imagine how a 40 pound block can exert 200 pounds of force and are thus drawn toward saying the forces between the blocks are unequal.

Following are tables 6 and 7 showing individual students' numerical responses to the two boxes problem. After these are two sections showing control and experimental student responses to the second parts of the two boxes problem, the part asking about the comparative sizes of the two forces. Only some of the control responses are included because

Table 6

Responses to the Two Boxes Problem:
Students Who Received the Control Explanation

Student	Existence	Conf.	Sense	Equality	Conf.	Sense
SC1	+	3.0	5	-	3.0	5
SC2	-	2.2	4			
SC3	-	2.3	4			
SC4	+	2.0	4	-	2.0	4
SC5	-	1.0	4			
SC6	+	2.0	3	-	2.0	3
Curt	+	1.0	2.8	+	1.2	3.7

Table 7

Responses to the Two Boxes Problem:
Students Who Received the Experimental Explanation

Student	Existence	Conf.	Sense	Equality	Conf.	Sense
SE1	+	2.0	4	+		4
SE2	+	3.0	5	+	3.0	5
SE3	+	1.5	3	-	2.0	4
SE4	+	3.0	5	+	3.0	5
SE5	+	3.0	5	+	3.0	5
SE6	+	3.0	5	+	3.0	4
John	+	2.5	5	+	2.5	5

these were the only subjects answering that an upward force exists in the first part of the question.

Control subjects. SC1 seemed to have misunderstood the question, interpreting it as asking to compare the force of the ground on the two boxes versus the force of the two boxes on the ground. He thus answered incorrectly that the forces would be equal. After an intrusive probe at the end of the interview, he changed his answer to the correct one. However, because of the intrusive nature of the probe, his first answer was used in scoring. The words "the earth just uses 150 pounds of force" seem to indicate that he was using a concept of force as a quantity which the earth "has" rather than viewing force as arising from an interaction.

SC1: I'd say it would be C because again, if, I mean you need enough force to move something, and the earth certainly has enough force to move 50 pounds, but it doesn't do it because of gravity. And, the 150 pounds does not have enough force to move the earth any distance, like, you know, down, so each, like both boxes exert a force 150 pounds downward and the earth just uses 150 pounds of force to keep it up, otherwise it would start sinking into the ground.

SC4 was the first student interviewed, and she received questions presented in a slightly different fashion as a one part rather than a two part question. Briefly, choice number two stated that only the ground exerts a force on the lower box, and choice number four was the correct answer. She had indicated earlier that she refused to accept the control explanation until the source of the force was identified, and she seemed in this section to consider the ground to be the source

of all the force in this situation, answering for the first time during the post questions that an upward force would exist.

SC4: I guess 2 [only the ground exerts a force on the lower box] would be the one I would choose. That's the most right.
I: Ok
SC4: And I'm fairly confident because I'm not really sure if we're defining the force as coming from the ground or coming from the upper box. I, I would say that it's coming from the ground, but I'm not a physicist.
I: Ok. And how much sense did that one make? Number two?
SC4: Um, I would give it a four.
I: Hm. Ok. And how much sense did number four make?
SC4: "Both the ground and the upper box exert forces on the lower box, but the ground exerts the larger force." That doesn't make any sense at all.

SC6 answered that the forces would be equal, giving as a rationale the following somewhat tangled explanation. It is interesting to note her references to the 50 pound box, the 100 pound box, and the ground as "less weight," "more weight," and "complete weight," indicating a concept of force as an innate or acquired property of an object.

SC6: Well, ok you figure the 50 pound one is on the 100 pound one, and the hundred's on the ground, so you're going less weight, more weight, and you know, you know, ground is like complete weight, so the ground is holding these two up. If you put these two boxes on, on a paper thin, um, desk, the desk will fall apart. But the ground is holding both of these up, the 100 pound is holding the fifty pound, and at the same time the fifty pound is pulling, they're pulling against, pulling towards each other, and the ground's holding both of them up, and, C both the ground and the upper box exert forces on the lower box, and these forces are the same size, um, well they're not, they're not the same size literally, but, I think the forces that they're pulling together are the same size.

Curt's response is discussed in more detail in the case study, but it is included here for completeness. He gave the correct answer, but it appeared to be because he was focusing on the area the top box covered versus the area the ground covered on the 100 pound box.

261 S: Because there's more area on the bottom of this box. There's more force pushed up on it. This bottom, the little base is faced right here. More force is being pushed on it, as in, not as much force is being pushed on these little separate sections of this box by this 50 smaller box. Um, that's why I said 'yes,' see how sure I was.

Only one of the students who had received the control explanation answered both parts of the two boxes problem correctly without intervention, and this student's reason was the specious one of comparative areas. The general impression is of students with very naive or confused conceptions of force. By contrast, the explanations of the students who received the experimental explanation seem to indicate a markedly superior facility with reasoning using the concept of force for this situation.

Experimental subjects. Although SE1 indicated that the ground would only need to exert 100 pounds of force upward on the lower box (rather than the combined weight of 150 pounds), his reasoning was based both on a direct causal model (the ground gives a little) as well as an indirect causal model exemplified by his reference to the hand holding the dictionary. Thus he appeared to be viewing force as an interaction between two objects.

SE1: Does the ground exert an upward force on the lower box? Yes, I mean, yes, cause it gives a little, and that prevents the table, I mean the box from sinking down into the ground so, and I'm fairly confident about that. And I said yes, and....Well, well I'd say that the, um, let's see, I'd say B, both the ground and the upper box exert forces on the lower box, but the ground exerts the larger force, cause it has to resist 100 pounds, and just like when you're holding the dictionary you have to, that weighs 30 pounds, you have to exert 30 pounds of force and while the, and the lower box is 50 pounds, so, it's exerting only 50 pounds on the box, well, on the lower box, while the ground has to exert the same amount of force

> that the lower box weighs, so, it exerts force on the lower box, I mean, it exerts the hundred pounds that the lower box weighs.

It is not possible to discern from this transcript segment what model SE2 was using for force, but the clarity of the description indicates good if not complete understanding.

SE2: The upper box exerts pressure on the lower box, the upper box exerts 50 pounds pressure on the lower box. Both the upper box and the lower box exert 150 pounds pressure upon the earth. The earth exerts in turn an upward force of 150 pounds upon the lower box. In other words, the earth is exerting a force of 150 pounds, while the upper box is exerting a force of 50 pounds so in those terms the answer would be B.

Throughout the post questions SE3 seemed to rely solely on indirect causal reasoning, and in this case it caused her some trouble. She seemed to think the forces would be equal on both sides of the lower box since the box is not going anywhere. A little later she added that a guess would be that each box is exerting 50 pounds of force to add up to 100 pounds (the weight of the lower box). Thus the indications seem clear that SE3 did not have a good understanding of force in this situation.

SE3: I guess that would be C, just because the forces of the two sides have to balance each other or else it would move, or the box wouldn't stay in one place.

SE3: Because they're each exerting 50 pounds of pressure both ways, it would equal 100, I don't know. That's a guess.

It is again not possible to discern the model SE4 used for his answer, but again judging by the clarity of the explanation, his understanding was also quite good.

SE4: Well I'd say B because the ground is holding, or forcing 150 pounds of force up, it's exerting 150 pounds of force upward, and the upper box is exerting a hun, 50 pounds on the lower box, so the ground is exerting the most force.

Prior to this segment SE5 had talked about the molecular structure of the ground being springy allowing it to exert a force upward on the lower box, indicating direct causal reasoning. The phrase "the upper box exerts a force on the lower box which is equalized there" indicates that he may have been using indirect causal reasoning as well. He had initially answered that the forces would be equal, but as he was explaining his answer, he changed to say that the ground would exert the larger force.

SE5: I would say, uh, actually I would say no on that, uh, because the upper box on top of the lower box, no wait, the upper box exerts a force on the lower box which is equalized there, but when you say that the ground is, has an equal force on the lower box that's incorrect because the upper box is on top of the lower box so it'd be more force, if you combine them together.

Although not exhibiting the clarity of presentation of some of the other student explanations, SE6's reasoning seemed to be roughly on the right track.

SE6: I'd say this, cause I think that along with, uh, the gr, the ground's force, I mean the upper, the upper box's force on the lower box, which would be 50 pounds, there's the force of the lower box pressing up, plus the force of the upper box, so that's another 150, so that's 150 pounds coming this way [from the ground to the lower box] 50 pounds going that way [from the upper box to the lower box].

John's answer is discussed in more depth in the case study. Notice the reference to the compression of the molecules (indicating direct

causal reasoning).

278 S: Um, the ground, the ground exerts an upward force because a hundred, actually 150 pounds worth of pressure is on the ground and compressing the molecules. The molecules are exerting 150 pounds worth of force back. And the ground exerts the larger force cause it's exerting 150 pounds worth of pressure whereas, um, whereas the higher box is only putting 50 pounds of pressure on the lower box.

In conclusion, six of the seven students who received the experimental explanation chose the correct answer on both parts of this problem. Further, the students' reasons on the whole indicated a facility with reasoning about force which seemed quite absent in the students receiving the control explanation.

Steel Blocks Problem

The impression that the students who received the experimental explanation had, in general, a superior understanding of the concept of force grows stronger after examining the students' answers to the steel blocks problem. This is a problem which almost requires a view of force as an interaction between two objects rather than as an innate or acquired property of an object due, for example, to its weight or state of motion. Under the latter view, the larger block resting on top of the smaller block would exert the greater force due to its greater weight. Following are tables 8 and 9 showing individual students' numerical responses to the steel blocks problem, and following these are transcript segments showing the students' reasons for their

Table 8

Responses to the Steel Blocks Problem:
Students Who Received the Control Explanation

Student	Existence	Conf.	Sense	Equality	Conf.	Sense
SC1	+	3.0	5	-	2.0	4
SC2	-	2.8	5			
SC3	-	3.0	5			
SC4	-	2.0	3			
SC5	-	1.0	3			
SC6	+	1.0	3	-	1.0	4
Curt	+	1.7	3	-	1.9	4

Table 9

Responses to the Steel Blocks Problem:
Students Who Received the Experimental Explanation

Student	Existence	Conf.	Sense	Equality	Conf.	Sense
SE1	+	1.8	4	+		3
SE2	+	3.0	5	+	3.0	5
SE3	+	2.0	3	-	1.6	3
SE4	+	3.0	5	+	2.0	4
SE5	+	3.0	5	+	3.0	5
SE6	+	3.0	5	+	2.0	4
John	+	1.5	5	+	2.0	3

answers. Again, only those students answering correctly the part about the existence of the force are included.

<u>Control subjects</u>. In the following segment, SC1 displayed very clearly that his concept of force was that of force as an innate or acquired property of an object, in other words, that objects can "have" force. Reasoning from this basic assumption he decided that the larger block on top would push the smaller block on the bottom into the ground because of its greater force.

SC1: I think it [40 pound block B on the bottom] exerts a force up, but I don't think it exerts enough to stop A [200 pound block on the top] from pushing B into the ground. See, it just makes the thing slower. So say B only weighed one pound, then A would have 199 pounds more than B would, and so it would push it into the ground faster. But this way, B has some force, it has a larger force than before, but not enough to keep A from pushing it down into the ground...Hard to think about this one because in the ones before where the light thing was on top, the heavy thing just used enough to fend off, you know, to keep the lighter thing on top. See, so it's a matter of how much force the thing uses. So I'd say that, uh, A and B exert a force on each other, but A exerts a larger force.

SC6 gave the same answer, that the 200 pound upper block would exert the larger force, and she generated a particularly compelling analogy to support her case, that of a 500 pound person squishing a 20 pound child.

SC6: I think [answer] A [block A exerts the larger force], because the A is 200 pounds and the B is 40 pounds so it, it's like if you put a 20 pound kid on a 500 pound person, you know, it, no, the other way around, it, the thing would squish.

Curt's transcript gives another comparatively clear case of reasoning under the assumption that force is an innate or acquired

property of objects.

275 S: Using weights makes me feel more sure about myself, ah, for some unknown reason. Maybe it's, maybe it's just because they're strewn out in front of me. But, um, so I'm more, I'm fairly confident that this box is putting up a resisting force to A which is more on top. If I said 'yes,' A and B, A exerts a larger force. That was, there. I would say that A and B exert a force on each other, but A exerts a larger force, more weight, and covers the entire face of this box, with 200 lbs. of pressure which is 160 more lbs. pushing down on the box.

These transcript segments seem to indicate that all three of the subjects were completely submitted to the assumption of force as a property of objects. None of them referred to Newton's third law, even though they had just read the control explanation about the third law, preferring instead to rely on their naive conceptions of force. By contrast, even though the students who received the experimental explanation were obviously bothered by the conception of force as a property, six of the seven resisted the conclusion of that assumption and answered correctly.

Experimental subjects. SE1 seemed to be struggling with the idea of objects having a certain amount of force when he referred to a lot of the force being held by the ground. However, he appeared to have resisted the temptation to attribute force to the objects based just on their weight. The phrase "it has to be equal to that challenge" implies that the conception of force he is using in this situation is that of force as an interaction arising when two objects "challenge" each other, a phrase which implies he may have been using indirect causal reasoning.

SE1: If you put like weight on a table, then it's going to resist that weight, but you could put a lot more than the table weighs, so, and a lot of the force is also being held by the ground or the floor. So, I'd say like A and B exert the same force, um, yeah, C, and that they exert the same size. Because if it was smaller, if um, A was smaller, it'd be just like the others, but this case, like it'd be just like a smaller force on a table, I mean a smaller weight on a table, but if you just increased the weight then like it has to be equal to that challenge and hold it up. So I think they exert the same size of uh, yeah, they have to equal the same size force on each other.

SE2 provided a classic example of how the experimental explanation could help students in this and similar problems. Although he initially answered correctly, he did have some trouble making sense of the problem. He initially struggled with the conception of force as a property and was unsure whether the 40 pound block could exert 200 pounds of force. The first section below indicates a struggle between the conception of force as a property and indirect causal reasoning pointing to force as an interaction (for SE2 "readjusting from the stress" is a way of expressing equilibrium reasoning). However, his confusion was dispelled when he thought of the book resting on the spring.

SE2: Alright I'm having trouble with this one because I'm thinking in terms of they both should exert force on, forces on each other because B has to readjust itself, it has to readjust from that stress, it has to relieve that 200 pound stress. However, it only weighs 40 pounds. Because of that number, um, I don't know whether it can do that.

SE2: Um, does B exert an upward force on A. Makes some sense to me. The reason it doesn't make perfect sense to me is because block A is so much more heavier than the other. Wait a minute...I, I'll have to change that. I've just thought about the instances of the book and the spring and of course the spring was, weighed so much less than the book but still the spring did boun, the spring did bounce back. Those atoms are still springy. What happened is that, you evil people, these boxes, when I look at them, are very deceiving. One looks so much bigger than the other, that one is

unsure that hey will B be able to exert that upward force, but of course it does. Even if one weighs, even if one weighs so much more than the other because sure, the book weighed so much more than the spring, but the spring did bounce, the spring bounded back, why can't the same thing happen to this?

It is interesting that SE3, who reasoned consistently throughout the post questions using indirect causal reasoning, would abandon this in favor of the conception of force as a property. Even though the section in the experimental explanation making use of indirect causal reasoning concepts was quite compelling for her, it apparently was not compelling enough in the face of this difficult transfer problem.

SE3: It exerts a force, but it's not a force equal to that, cause that'll, I mean, because like when you have the book on your hand you have to exert a equal force for it to be the same, but for this one, the upper one has more, can push down with a greater force than the lower one can push up, but it still exerts an upward force. Um, A exert, well, A yeah, I think it's A and B exert a force on the other but A exerts a larger force.

Although SE4 chose the correct answer, he toyed with answering that block B would exert the greater force, perhaps because B would have to fend off 200 pounds of force whereas A would only have to fend off 40 pounds, reasoning which also indicates relying on the assumption of force as a property. However, by relying on indirect causal reasoning, that is, thinking of the blocks reaching an equilibrium, he chose the correct answer.

SE4: Both are exerting force on one another, um, B could be exerting a larger force, but you, you don't know. It's either equal to or greater than. But I guess they'd reach an equilibrium, so they're both exerting the same amount of force.

SE5 is the only student who gave no indication of considering the concept of force as a property. He gave a quite straightforward answer based on the "spring theory."

SE5: "Each exerts a force, and these forces are the same size." Yes. Uh, cause the B block weighing, uh, let's see, they would give a little, and so would the A block, so, yeah, they're both exerting force upon each other, going back to the spring theory.

SE6 indicated that the mass of the blocks was a consideration for him, but he indicated thinking of force as an interaction when he said "we're talking about the blocks on each other."

SE6: And if I said yes, I'd say that A and B exert, I'd say it's an equal force because, unless again, unless you're talking about mass, it's an equal force just because there's, uh, we're not talking about the ground, we're talking about, we're talking about the blocks on each other and since there's, there's nothing, there's no difference really between them since they're both, well, yeah, there's no real difference between them.

For a more complete transcript segment of John's reasoning on the steel blocks problem, see the case study or appendix C. He also struggled with the idea of force as a property, but the idea of the molecules compressing, as well as a desire to be consistent with the written explanation, swayed him to answer correctly.

283 S: Well B exerts..200 pounds worth of upward pressure on, uh, A, cause the molecules compress, actually, well actually that really doesn't make that much sense to me, but I'm putting it down because of this here [the explanation].

In conclusion, it appears that the concept of force as an innate or acquired property of objects is both widespread and resistant to change. All three of the students who received the control explanation

and who answered the first part of the steel blocks problem correctly based their answer for the second part of the question on this assumption. Six of the seven students who received the experimental explanation indicated considering this conception of force while answering the second part of the steel blocks problem, and one of these rejected the indirect causal argument, which had previously been quite compelling for her, in favor of this conception of force. However, the fact that six of the seven students who received the experimental explanation answered both parts of the problem correctly indicates that they were given a way of thinking about the situation which enabled them to veer away from this seductive view of force to the more appropriate view of force as an interaction.

Reasons for Differences

There appear to be some strong reasons to suspect that the experimental explanation was more effective based both on students' numerical responses and students' reasons for their answers. Examination of the protocol data indicated some possible explanations for the differences in student reaction to the two methods of using thought situations. In order for students to make sense of situations for which they have a misconception, it appears that they must draw on and extend existing intuitions rather than simply memorizing counter-intuitive principles. To help students in this constructive effort, first, the examples used must make sense to the students, not simply to the teacher or textbook author presenting them. Second, even

when an example is compelling to the student, it may not be seen as analogous to the target problem in the lesson, in which case the analogy relation would need to be explicitly developed. Third, it may be important to develop qualitative models which give mechanical explanations for phenomena. Examples from protocols which support each of these factors are given in the next three sections.

Examples Must Make Sense to the Students

Several of the examples in the control explanation made little sense to some of the students. The segments below illustrate typical student responses for the two examples of the ground pushing forward on the runner and the stone pushing on the finger. First, two example responses are given to the second paragraph which contained the example of the athlete running, saying the ground pushes forward on the athlete.

I: What are you thinking?
SC4: That the ground isn't doing any pushing, all it's doing is just sitting there.
I: Does it make sense to you that the ground pushes forward on the athlete?
SC4: No, because why should the ground all of a sudden just spontaneously decide to push forward when there's somebody running on it, but it doesn't push forward when there's nobody running on it?

SC5: The, the push of the ground forward on her doesn't really seem to exist. To me it's more of her, it just seems to me like her feet are pushing against the ground and there is, there's an equal um, and the force of the ground, I guess you could say it pushes back, but actually it's not really pushing, it's just her that's pushing. So I don't know. It seems like their way of describing it sort of doesn't make that much sense to me.
I: Does it make sense to you that the ground pushes forward on the

athlete?
SC5: No, no.

Following are the same students' responses to the example of the stone pushing back on a finger pressing on it.

I: Does it make sense to you that the stone would push back on the finger?
SC4: No, because it's done on a stationary object. It's, um, being held stationary by gravity, but if the finger didn't exert any force on the stone then the stone wouldn't start pushing the finger around.

SC5: That doesn't make very much sense to me because if one object is say, fixed into the ground or it can't be moved and the object is moving and pushes against it, it sort of, it seems to me that the push is coming from the object that's moving and pushing against the object, and the other object is just exerting a stationary force, but it's not exerting a push or a pull, it's just there so it, there's force coming from it being stationary and not being able to move it. But it doesn't seem like there's mutual pushes and pulling going on all the time in the interactions.
I: Does it make sense to you that the stone would push back on the finger?
SC5: Um, not really.

By contrast, most of the students indicated the examples in the experimental explanation made a great deal of sense. Following are two example transcript segments of students talking about the situation of the hand pressing down on a spring.

SE1: What was I thinking there? I think that, um, that the spring probably, when you push down on it, it would have some force going back up, cause it's like pushing back on the, um, like if you let go it springs back up, so it's, yeah, and if you put like, yeah, press down and it's like trying to, it's resisting it and like pushing back upwards, it wants to go back up as soon as you let your hand off.
I: Does it make sense to you that the spring would push back up on your hand?
SE1: Yeah.

I: Does it make sense to you that the spring would push up on your hand?
SE4: Mm hmm, that's, yeah, I base, I can reason that out.
I: Umm, what sense rating would you give there?
SE4: Five.
I: Five. Could you say a little bit about what's behind your sense rating?
SE4: Well, I know that certain metals are more, um, have elastic qualities to them and they're able to be bent, and they desire to go back to their original position so they'll exert however much force they're capable of to, to try to get back to that previous position, and then the force I'm putting on it will move it down, and the metal structure, assuming it's a metal spring, will try to retain its old position.

As can be seen in tables 10 and 11 the average sense rating for the control examples was 3.27 out of 5 (the examples made slightly more than some sense to the students), whereas the average rating for the experimental examples was 4.60 (the examples made slightly less than perfect sense to the students). This difference is significant at $p < .001$. However, as the following section shows, simply having good individual examples may not be sufficient for understanding.

Need to Develop Analogy Relations Explicitly

Many teachers and textbook authors supplement their presentations with analogous examples. However, perhaps because the situations are to them "obviously" analogous, no attempt is made to explicitly develop the analogy relations. The present study indicates that the use of thought situations in this way may be ineffective. For example, even though the physicist views the book on the table and the hand on the spring as completely analogous situations, six of the seven students given the experimental explanation did not. Two examples are given below.

Table 10

Average Sense Ratings: Control Explanation Examples

Example	Average sense rating
Runner	2.14
Finger on stone	2.71
Rowboat	4.00
Car	3.14
Rifle	4.14
Balloon	4.43
Apple	2.33
All together	3.27

Table 11

Average Sense Ratings: Experimental Explanation Examples

Example	Average sense rating
Hand on spring	4.71
Book on spring	4.57
Spring force 10 lbs.	4.43
Book on board	4.71
Book on foam	4.57
All together	4.60

I: Is this different from the book on the table?
SE1: Yeah, because if you were pressing down on a table, couldn't you like, I mean, if you like, lose some of your force, like just relax a little bit, your hand's not going to go springing back up like on, like if you were pressing down on a spring. If you were pressing down on a spring, you press down, and you let go just like, a little bit, like you eased up, your hand would just go up, ah, it would be pushed up.

I: Is this different from the book on the table?
SE4: Yeah, I guess in a way in my reasoning it seems like it would be. That, the table is not forcing back because of its, I guess its structure, its molecular makeup, it's not exerting a force to retain it to its, it's not forcing, er, it doesn't have any force to push back up.

However, when the analogy relation between the hand on the spring and the book on the table was developed, every subject indicated that this analogy was helpful in making the idea of an upward force from the table make sense. Following are some transcript segments in which the students clearly indicated in retrospective comments that a specific comparison or series of comparisons was helpful.

SE2 not only appreciated the sequencing of the analogies, he went as far as to suggest a slight alteration in the order by switching the presentation of the flexible board and the foam rubber. Such a suggestion indicates that he understood the strategy enough to propose improvements.

SE2: The images that all helped were all of them. The image of the book on the spring, the image of the book with the hand, the book with the board, and the book with the foam rubber. Because the ideas of, uh, elasticity, of, of atomic bonds, were made visually, for example, the elasticity of atomic bonds were made visually apparent in those four preceding images, and that as my mind, or my intuitive sense gave me hypotheses, um, I found evidence to support my hypotheses in the next image after it.

SE2: They all made sense, but there were, but one of them was not in

the correct order...For the the third image on this page, I would have substituted the foam rubber and put, um, the board and the table on four.

SE4 found the comparison between the spring and the flexible board to be helpful.

SE4: Everyone assumes that a spring is exerting a force because they can see it, and that it actually does force things back if you push on it or something, and that then that moves on from a spring to say a board and most people know that a board exerts force if you put it between something and push it in the middle, and if it's a flexible board you'll see it bend and you'll see it force its way back.

SE5 also found the comparison between the spring and the flexible board to be helpful.

SE5: The part, let's see, I, I sort of figured that out cause this is sort of a spring, they, when they have the two um, sawhorses, and the board over it and they show a picture of it springing inwards you know and denting sort of with the book on it, and uh, they showed up here the spring which is compressed by the book's weight on top of that, um, and then they showed a normal spring. I guess it, it sort of, got across to me uh, both being springs, so, it's pretty good.

John said that the entire sequence was helpful for him. (See the case study for more detailed comments).

191 S: I don't think the spr.., well, I guess I didn't think the spring helped, but in context I guess..out of context you just compare the spring and the table it wouldn't help, but you sort of built a way up from the spring, which is obvious, to a flexible board, to a not so flexible board, to foam rubber, to a table, which is pretty good.

The above segments show that for at least some of the students, the comparisons between the examples in the experimental explanation

were important in the development of their understanding of how a table could exert an upward force. Following are a few transcript segments showing analogical reasoning in "real time" as the students interacted with the explanation.

Five of the seven students indicated explicitly that there was an analogy relation between the hand on the spring and the book on the spring. Even though this relationship may seem obvious (in past interviewing experience this has not always been the case) the explicit mention of this relationship showed a willingness to engage in analogical comparisons. In the following example, SE3 not only indicated that she saw the book on the spring as analogous to the hand on the spring, she showed that she knew the purpose of the book on the spring was as an intermediate or bridging analogy.

SE3: "Now consider the case of a heavy dictionary being placed on a bedspring so the spring compresses some."
I: What are you thinking?
SE3: Well, it's just, it's basically the same as pushing on it with your hand, so that I'm not really thinking anything different.
I: Ok
SE3: It just sort of to show you that changing from a hand to a book cause this is about putting a book on a table.

In the following segment, although SE6 said he felt the situations were analogous, he said there was a difference in that there was no way to feel the force in the situation of the book on the spring.

SE6: "Now consider the case of a heavy dictionary being placed on a bedspring so the spring compresses some." Ok, there you have your model, the spring actually demonstrating the, uh, the principle of force being exerted down, pressing down, and you can't see it the way you can feel it, I think, with the, uh, the hand on there that the, that force is also being, um, exerted upwards. I mean, you can't, you can't actually realize that force is being exerted upwards, cause there's no way to tell, because you can actually

feel the spring on your hand, like poking into your hand, when you're using it with your hand, but when you got the book on there, it's just sitting there and you're, I mean you're not interacting with it at all.

I: Does it make sense to you that the bedspring pushes up on the book?

SE6: Yeah, it does, cause if, it makes sense that it pushes up on the hand, it's just a different object.

In addition, before reading the paragraph about the book on the spring, two of the students (SE1 and John) generated their own intermediate analogy between the book on the table and the hand on the spring. In both cases this was the case of a hand pressing on the table. For both of these students, they saw this situation as analogous to the book on the table but not to the hand on the spring as they both maintained that the table would not press up on the hand. Thus it appears that the students were quite willing and able to engage in analogical reasoning in a way that they might not be with, for example, deductive reasoning with formal algebraic manipulation.

As another example of a student generated bridge, in the following segment, after reading the third paragraph in the experimental explanation, SE1 responded to the question of whether the book on the hand was different from the book on the table with the following chain of intermediate analogies demonstrating that the situations were not analogous. This innovative student generation of intermediate analogies is illustrated in figure 5.

SE1: If you were putting that heavy dictionary, and then suddenly with the same force in your hand the dictionary was replaced with like a paperback, your hand would go up, so, but, well, no matter how small you put an object on the table it's not going to go up.

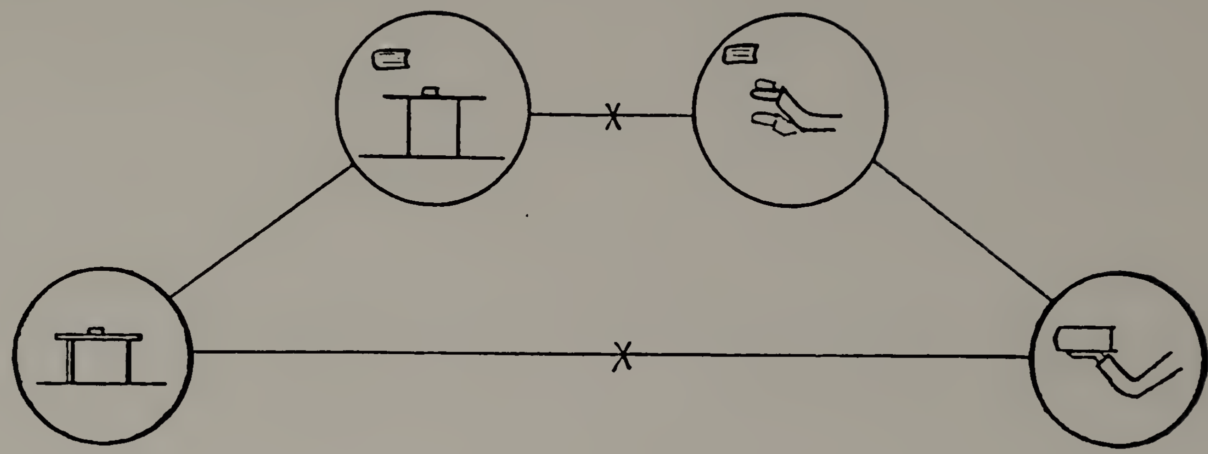


Figure 5

Example of Student Bridging Analogies

The following transcript segment gives some evidence for the ability of intermediate analogies to cause conceptual conflict if the student is unsure in which of two previously separate categories to include the intermediate analogy. When asked why his sense rating for the book on the spring was not higher or lower (it was a 4), SE2 gave the following reason for why it was not higher (his sense rating for the hand on the spring was a perfect 5).

SE2: (Long pause) Conflict of images. The first example, or first image, where I was asked, does the table exert force upon the book, I'd say oh yes of course a table doesn't exert an upward force upon the book. But now I see a different image where the spring is exerting upward force upon the book, and because I now see a new image contrasting the first image of the book on the table, now I'm not so sure that an object can or cannot put an upward force upon another object. So that's why I'm saying quite a bit of sense to me, and not perfect.

The fleeting reference in the experimental explanation to the continuous transformation of the flexible board to thicker and thicker boards brought several comparison responses shown below. SE1 related the thicker board to the table, SE5 related it to a stronger spring, and SE6 related it to the mosquito and Washington Monument problem.

I: Is the book on the board situation different from the book on the table?

SE1: I guess so, no, it's about the same, cause if there, if there's imagine a thicker board then you can just imagine a table as a thicker board, so it's not that much different.

SE5: Well, I guess thicker boards would be a stronger spring, it wouldn't have to bend as much, looking at this. So I guess it's hard to detect, um, how much the board, you know, compresses, you know, where it gives to the book until it makes an equal uh, force of weight on both sides.

SE6: Just because the boards are thicker doesn't mean the force is getting any less, it just means it can support it better. That's what I think about that. Same, I mean same with all of these, same with the uh, Washington monument and mosquito.

When SE2 read about the flexible board, he was puzzled that the board would not flex back to being perfectly straight in its attempt to regain equilibrium. After reading the paragraph about the foam rubber, he generated his own intermediate analogy between the board and the foam rubber of a ball in water; "the water gets pushed up more on either side of the ball or in all directions around the ball." This helped him to realize that the board would not have to return to its original position in order to exert force.

I: How much sense does it make to you that the foam rubber pushes up on the book?

SE2: It makes perfect sense to me because even though the foam rubber is not perfectly level like it was before the book came in contact, perhaps its, um, perhaps it has still fully readjusted even though it is not perfectly straight again because the atoms, or whatever you want to call it, have been moved over to the sides, um, sort of like Archimedes law with the ball in the water. The water gets pushed up more on either side of the ball or in all directions around the ball. Um, and with that in mind I can go back to the board and the book and say even though the board is not perfectly, even though the board has not, uh, bounced back to where it is perfectly straight, um, I can say now that the book and the board make perfect sense to me.

In conclusion, their were several indications that students reason naturally with analogies and that the establishment of analogical connections was important to learning. Following are some indications that analogical reasoning was natural for the students.

- Five of the seven students indicated spontaneously that they saw an analogy relation between the hand on the spring and the book on the spring. This demonstrates a facility with analogical reasoning.

- There were a number of instances of spontaneous student generated analogies.

- Many of these spontaneous analogies were intermediate analogies generated while thinking about the comparison between two situations.

The following points indicate that the establishment of analogical connections was important to learning.

- For six of the seven students, the anchor alone was not sufficient to produce change, even though it made a great deal of sense to all of the students. These six students indicated that they did not initially view the hand on the spring as analogous to the book on the table.

- After some analogical connections had been developed in the explanation, all of the students indicated that they saw at least one of the later situations, before the molecular model, as analogous to the book on the table.

- In several retrospective comments students specifically indicated that they found the development of analogical connections to be important.

- In at least two cases, students indicated in these retrospective comments that the ordering of examples was important. One student went as far as to suggest a change in the ordering to make the teaching strategy more effective.

These points demonstrate both the willingness of students to reason analogically and the importance of such analogical reasoning. In all there were ten student generated analogies from the seven students interacting with the experimental explanation, five of which were student generated intermediate analogies or bridges. It seemed to be quite important to the students' understanding that they themselves perceive the analogy relations. From the above results, it appears that the attempt to develop analogy relations explicitly in the experimental explanation was a contributing factor to the differences in student performance between those interacting with the control explanation and those interacting with the experimental explanation.

Mechanistic Models are Important

The experimental explanation also gave students a mechanistic model for the source of a force from a table, the table as composed of molecules connected by springy bonds compressing on contact with other

objects. This model gives students a reason for why the table exerts a force, the microscopic compression or bending of the table. Such a mechanistic model was lacking in the control explanation. The absence of a source or agency for the force troubled several of the students as was seen earlier in their reasons for their rejection of the conclusion of the control explanation. This sentiment is pointedly illustrated by the segment below.

I: Can you summarize the main idea of this explanation?
SC4: Um, well they're trying to tell me that, um, for every force there's an opposite force that happens against it. But they still haven't told me where it comes from or why, and I have no intention of accepting it until they do.

The absence of a mechanistic model may have led students to think about force in their usual way, which often meant thinking of it as an innate or acquired property of an object rather than arising as a result of an interaction. Several examples of such thinking in the steel blocks problem were presented earlier. This is a problem for which many students answer that the larger block exerts the larger force because it "has" more force. By contrast the students who received the experimental explanation, although they struggled with this naive conception of force, for the most part considered force as an interaction.

Agency for Force Important to Students

As we have already seen, most of the examples in the control explanation made little sense to the students. The rowboat example was

one interesting exception to this norm. As the following segments show, a majority of the students found this example to make sense because they saw in the possible motion of the water a source or agency for the force. By contrast, they did not see such a source or agency in the ground.

SC3: Well, the rowboat can make sense, but the car, I still, I can't you know, understand how the ground could be pushing up against something. It's just, it can't move at all. The water can move. The water can be moved, it's not just sitting in one position like the ground. The ground can't move, but the water can move by air or by the oar. And with the car, like I said before, the ground can't move, and I don't see how it would be able to push up against the tires.

SC5: I can see the water, I can sort of understand the idea of the water pushing forward on the oar while the oar pushes back on the water just because it's, it's um, it's not a solid stationary, water's not solid and stationary, and so it's capable of motion and force that seems equal to the, to the force of the oar, and I don't understand the ground exerting a force on the tires with the car as much just because the ground is just there, and it's flat and stationary, and it doesn't seem capable of exerting a force except for its, its force of, of uh, not giving away, and just being a solid object.

SC6: I get the boat. If you're on a boat and you don't have a motor or propeller or anything you can just sit there but the boat can still move. But the car I don't get, because it's obvious that the car is set in motion by the push of the ground on the tires as they push back on the ground.

135 S: Ah, the rowboat makes probably quite a bit of sense.
136 I: Okay.
137 S: I understand because of the water currents. Ah, the tires make some sense to me, but I haven't fully understood the friction not sufficient yet, but I'll get a better understanding of that, any second now.

Another interesting example of a student looking for an agency for force comes in the following segment. SC4, the first student to be

interviewed, had a slightly different explanation which included in the paragraph about the rowboat and the car another example about a tennis racquet striking a ball (the wording for this example came from the caption for a diagram included with the excerpt in the physics text from which the control explanation was taken). This example was subsequently removed from the control explanation because the compression of the tennis racquet made the example too similar to examples in the experimental explanation.

Previously, SC4 had indicated that the finger on the stone example made little sense to her because she did not see where the force could come from in the stone. In the following excerpt, she spontaneously related the tennis example with the stone example and transferred some understanding from the tennis example to the stone example via an analogy relation.

SC4: Ok, now that makes more sense than the rock analogy, that, even though it's the same principle, because I can readily identify the fact that, um, there's a force happening in the tennis racquet because somebody's holding it and swinging it, and I can identify the fact that there's a force happening in the tennis ball because somebody just hit it over from the other side, and therefore they have two forces that are happening against each other. And so now the rock analogy makes much more sense because I can see that, that, um, what's happening to the rock is, like, the equivalent of the person holding the tennis racquet is the gravity holding the rock.

I: Ok, you were talking about the tennis racquet and the stone. I was just wondering how you were relating those two.

SC4: Well, it seemed to be the same principle where there's a force that's acting on the, the tennis racquet or that's causing a tennis racquet to act, and the same thing with the stone, and then there's an opposite force happening to both of them which is the hand and the tennis ball, but that it's a lot easier for me to understand it when I can identify where the force comes from, rather than just having to accept that it's there.

I: Uh huh. And so where does the force come from in both cases?

SC4: Well, in the tennis racquet it comes from the person that's

swinging it, and in the rock I suppose it comes from gravity, but I never really understood where gravity came from, so it makes a lot less sense.

Model of Force Due to "Springiness" Important to Students

From the above quotes it appears that when a force is said to be present in a given situation, students want to know where that force is coming from, that is, what the agency is which is responsible for the force. Unlike the control explanation, the experimental explanation attempted to answer that question with the model of the table as springy and with the deeper model of the table as composed of molecules connected by springy bonds.

Student reaction to the molecular model was mixed. Four of the seven found the model to be quite important to their understanding (SE2, SE4, SE5, and John), one indicated that it was marginally helpful (SE1), one said that it would have helped if she did not already know about it (SE3), and one said it was not helpful since he accepted the upward force even if the table were rigid (SE6). A few examples are given below. First, two students who found the molecular model very helpful.

SE2: When I first saw that image with the table and the book, because of what was visually apparent to me I didn't say that there was a force exerted upward by the table because I can't see things with my own two eyes at a microscopic level. However once I am exposed to that image of the springs, and most importantly the image of the springy bonds between the molecules, once I've seen this image of the molecules and the springy bonds then I can go back and look at the table and the book and concur with you and agree to the idea of the table exerting upward force upon the book, because in my mind I'm thinking in microscopic terms. So to me these images are really, really important, um, in developing internally, um, the correct answer and concept.

I: Ok. And let me ask if you could just rate how much, uh, does the explanation help the idea of an upward force from the table make sense, on a scale from one to five.

SE4: Yeah, five, because there, there's an explanation of the molecular makeup and the reasoning behind why the table is actually resist, it's actually providing a force back on a molecular, at a small scale, the, even the stiff board and the stiff table is providing a force upward...The molecular makeup's good for reasoning the whole thing out.

However, SE6 did not find the molecular model helpful as he said that he would think there was a force even if the table were rigid. The following excerpts come right after he had read the summary paragraph, and then when he was asked which examples helped the idea of an upward force to make sense.

SE6: Now that sort of made sense to me even before I knew about the molecular idea at all, it just seemed that even if it's not squishy, force still exists, even if this table here is completely rigid, I don't see why the force wouldn't exist anyways.

SE6: The molecular idea seemed just to explain an idea that I already accepted so I didn't really feel that that was too important.

SE6 is the only student for whom there is no evidence that at least the concept of springiness was important. Even for SE6, he began to talk about the "inherent springiness" of the table in his answer to the post table problem and then wondered if was necessary to talk about that. Even though the molecular model was important for some students, it appears that even more important was the demonstration of the table as springy. As the above quotes illustrate, the molecular model was important to students because it gave them a way to "reason the whole thing out." To the question, "how can the table push?" the explanation answers "because it is springy." To the question "how can a table be

springy?" the explanation answers "because it is made of molecules connected by springy bonds." In a similar vein, Miyake (1986) discusses various levels at which subjects attempted to understand the operation of a sewing machine.

Thus the molecular model answered a deeper question than some students may have asked. Even without the molecular model, the experimental explanation provided a source for the force from the table, the table's small amount of springiness or bendiness, as well as providing indirect causal models of the book on the hand and the book on the spring arguing that there must be an upward force to balance the downward force of the book's weight. These models (the direct causal models of the table as springy and as composed of molecules with springy bonds, and the indirect causal models of the hand and the spring balancing the book's weight) draw on students' causal reasoning and intuitions in a way that the control explanation did not.

Conclusions

It appears from the results of the interviewing study that students' minds are far from being blank slates waiting to be written on. Five of the seven students who initially answered the table problem incorrectly and who received the control explanation simply refused to change their minds despite the fact that the explanation explicitly stated the correct answer and gave supporting examples. This result was quite surprising. Before conducting the study I was unsure whether to include the book on the table problem as a post

question because both explanations gave the correct answer explicitly. This surprising refusal on the part of the control students indicates that they had robust concepts about forces from static objects, even though it is unlikely that they had consciously considered the question previously. Since the students were given no reason to suspect that the explanation might be in error, the refusal of most of the students receiving the control explanation to accept the conclusion of the explanation provides striking evidence for the ineffectiveness of simply telling students the correct answer - even with supporting examples - in an attempt to effect conceptual change.

In light of such persistent naive conceptions, student interaction with the experimental explanation was surprisingly effective in bringing about change. There is also evidence to show that not only were the experimental students' conceptions about forces from static objects changed, their reasoning about force seemed more sophisticated than the reasoning of the students who interacted with the control explanation. In brief, the reason for these differences seemed to be that the experimental explanation successfully grounded the instruction in the students' intuitions whereas the control explanation did not.

The control students as well as the experimental students seemed to find it important to identify a source or agency for a force. In the experimental explanation, the table was shown to be springy, thus providing an agency for the force, whereas in the control explanation, no such agency was provided. By tapping into the students' intuitions with a conceptual anchor (the hand pressing down on a spring) and successfully demonstrating the analogy relation between this anchor and

the target problem, the experimental explanation demonstrated the agency for force, the springiness of the table. For those students who required a deeper explanation, the molecular model gave them a way of thinking about "rigid" objects as springy.

CHAPTER V

WRITTEN INSTRUMENT STUDY

Method

Subjects

The population for this study was the chemistry classes at a New England high school different from the one in which the interviewing study was conducted. As in the other high school, chemistry is taken by most students before physics, and so the population was representative of students who eventually take physics, but who had not yet studied physics. For this study, 110 students each received one of three possible explanations (described below). In each class the students were randomly selected to receive one of the three explanations.

The Instrument

For the written instrument study, I used the same two explanations (plus an additional explanation described below), but in a purely written format to allow for a larger number of students to participate. (See appendix D for the instrument.) For both explanations each paragraph of the explanation occupied a single page. In this way it

was possible to monitor accurately the ongoing effect of the explanation without fear that the student would glance down the page to an upcoming paragraph or diagram. Each diagram was included on the page of the appropriate paragraph. After most paragraphs students were asked to respond to a question in writing, rate how much the example(s) in the paragraph made sense, and indicate their current belief about an upward force from the table.

The third explanation was also identical to the experimental explanation of the interviewing study except that the references to the molecular model were deleted, along with the diagram of the molecules with springy bonds. This explanation was included to explore the question of how important the molecular model is to student understanding.

The questions were identical to those asked for the interviewing study with the exceptions that the runner problem was substituted for the mosquito problem in the post questions, and only the goat and table problems were asked as pre questions. As in the interviewing study, each question asked the student to rate his or her confidence in the answer given, but sense ratings were acquired only for the book on the table problem. Written student explanations were only requested for the pre and post table problems.

Quantitative Analysis

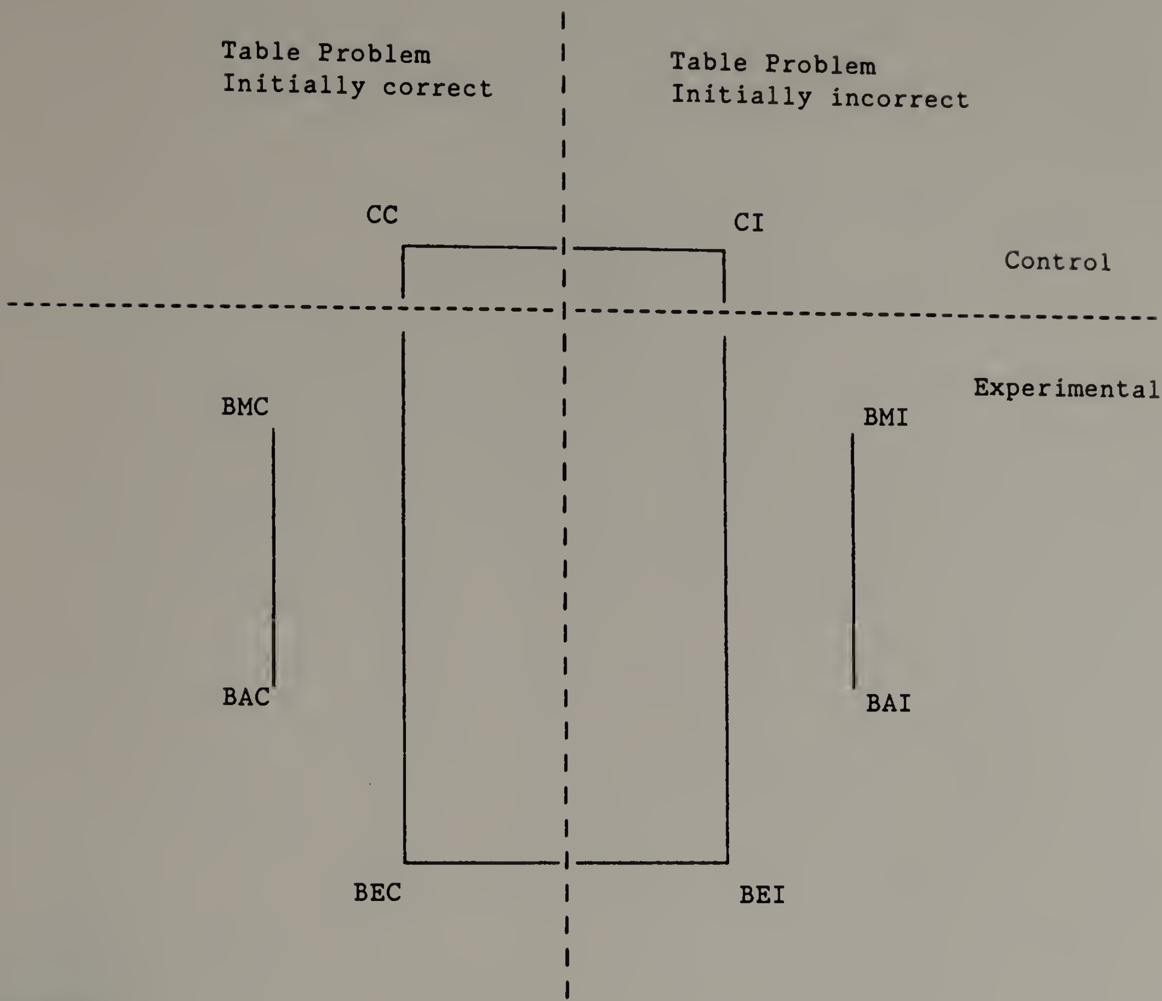
In all there were eight different groups which could conceivably be compared for group differences (the control group, the two

experimental groups, and both experimental groups taken together, further divided into those students who initially answered the table problem correctly or incorrectly). In an attempt to avoid a proliferation of comparisons (and thus increase the chances of false positives on significance tests) I made only those comparisons which were motivated by prior concerns.

Figure 6 diagrams the six comparisons made. These were: the two experimental groups to see if the presence of a model produced significant differences (BMI vs. BAI and BMC vs. BAC); the control group with both experimental groups taken together to see if the different approaches produced significant differences (CI vs. BEI and CC vs. BEC); and the control and experimental groups (students initially answering the table problem correctly) with the corresponding control or experimental group in which the students initially answered the table problem incorrectly (CC vs. CI and BEC vs. BEI). These last comparisons would indicate whether student reaction to the explanation depended on whether they had initially answered the table problem correctly or incorrectly.

The comparisons made were between performance on post questions (average percent of correct answers and confidence and sense ratings), student ratings of how understandable and believable the explanation was and how much the explanation helped the idea of an upward force from the table make sense, and the students' sense ratings of the examples in the explanations. Confidence ratings were considered to be positive if the student answered the question correctly and negative if the student answered the question incorrectly. In this way, a

COMPARISONS MADE: WRITTEN INSTRUMENT STUDY



LEGEND

CI Control, table problem initially incorrect
BMI Bridging plus model, table problem initially incorrect
BAI Bridging alone, table problem initially incorrect
BEI Both experimental together, table problem initially incorrect
CC Control, table problem initially correct
BMC Bridging plus model, table problem initially correct
BAC Bridging alone, table problem initially correct
BEC Both experimental together, table problem initially correct

Figure 6

Comparisons Made in Written Instrument Study

confidence rating of 2.0 for a correct answer would be a +2.0, whereas a confidence rating of 2.3 for an incorrect answer was considered to be a -2.3. The non-parametric Mann-Whitney test (similar to a two-tailed t-test) was used for all of the pairwise comparisons.

Qualitative Analysis

In addition to multiple choice responses and numerical ratings, students were asked to give reasons for their answers on the pre and post table problems and to answer questions after most paragraphs while interacting with the written explanation. These written responses were taxonomized and provided additional insights into students' reasoning and the effect of the explanations on students' reasoning. Students were also asked to indicate their current belief about the presence or absence of a force from a table on a book resting on the table after reading each paragraph. This information was quite useful for seeing when students' changed their minds about the book on the table problem, giving further information about their interaction with the explanation.

Results of the Quantitative Analysis

The first comparison considered is that between the two experimental explanations. The "bridging plus model" explanation was identical to the experimental explanation of the interviewing study, but in the "bridging alone" explanation the references to the molecular

model were removed, including the diagram. This amounted to the deletion of only two sentences in the sixth paragraph and a phrase in the seventh paragraph, and the number of questions the students were asked to respond to was not diminished, so the explanations were still roughly equivalent in terms of length and amount of student interaction. As tables 12 and 13 show, although the students interacting with the "bridging alone" explanation tended have slightly higher numerical scores, there were no significant differences between the two groups BMI and BAI. Tables for the comparison of BMC and BAC are not included because only the main result of this comparison (that there were no significant differences between BMC and BAC) is of interest.

Because there appeared to be no difference in student response to the two experimental explanations, the control explanation group was compared with both experimental explanation groups taken together. As can be seen in tables 14 and 15, there were no significant differences in performance on the post questions (with one important exception), but there were some differences in favor of the experimental explanation in the students' ratings. The problem in which there was a significant performance difference was the part of the two boxes problem asking the student to compare the relative sizes of the forces to be compared, for which the correct answer is that the forces are not equal. The extremely low percentage of students answering correctly for the control group on this problem (14%) indicates that many control students may have been answering the questions based simply on a memorized rule, forces always equal and opposite, without any deeper

Table 12

Comparison of Overall Performance:
Experimental Explanations
(Students Initially Answering Table Problem Incorrectly)

	BMI Bridging + Model (n=20)	BAI Bridging alone (n=20)
Pre-post differences (% increase)		
1) TABLE	90	95
2) GOAT		
Existence	50	70
Equality	55	55
Post scores (% correct)		
3) RUNNER		
Existence	84	95
Equality	63	65
4) TWO BOXES		
Existence	79	90
Equality	42	60
5) STEEL BLOCKS		
Existence	80	100
Equality	50	40

Table 13

Comparison of Student Ratings:
Experimental Explanations
(Students Initially Answering Table Problem Incorrectly)

	BMI Bridging + Model (n=20)	BAI Bridging alone (n=20)
<u>Average ratings increases</u>		
1) TABLE		
Confidence	4.46	4.79
Sense	2.45	2.72
2) GOAT		
Existence (confidence)	2.68	3.12
Equality (confidence)	2.64	2.54
<u>Average confidence ratings</u>		
3) RUNNER		
Existence	1.79	2.07
Equality	.27	.38
4) TWO BOXES		
Existence	1.51	1.99
Equality	-.04	.90
5) STEEL BLOCKS		
Existence	1.56	2.24
Equality	-.26	-.80
<u>Student ratings of explanations</u>		
Understandable and believable?	4.20	4.20
Helps to make sense?	4.30	4.55

Table 14

Comparison of Overall Performance:
Control Versus Both Experimental Explanations
(Students Initially Answering Table Problem Incorrectly)

	CI Control (n=21)	BEI Experimental (n=40)	
Pre-post differences (% increase)			
1) TABLE	86	93	
2) GOAT			
Existence	43	60	
Equality	57	55	
Post scores (% correct)			
3) RUNNER			
Existence	86	90	
Equality	67	64	
4) TWO BOXES			
Existence	81	85	
Equality	14	51	*
5) STEEL BLOCKS			
Existence	86	90	
Equality	52	45	

* $P < .05$ Difference in favor of the experimental group

Table 15

Comparison of Student Ratings:
Control Versus Both Experimental Explanations
(Students Initially Answering Table Problem Incorrectly)

	CI Control (n=21)	BEI Experimental (n=40)
Average ratings increases		
1) TABLE		
Confidence	3.71	4.62 **
Sense	1.85	2.62 *
2) GOAT		
Existence (confidence)	2.23	2.84
Equality (confidence)	2.17	2.74
Average confidence ratings		
3) RUNNER		
Existence	1.63	1.93
Equality	.46	.33
4) TWO BOXES		
Existence	1.37	1.76
Equality	-1.09	.46 *
5) STEEL BLOCKS		
Existence	1.59	1.90
Equality	.32	-.53
Student ratings of explanations		
Understandable and believable?	3.65	4.20 *
Helps to make sense?	3.62	4.43 *

* $p < .05$ Difference in favor of the experimental group
** $p < .01$

Table 16

Comparison of Overall Performance:
Control Explanation Given to Students
Initially Answering Table Problem Correctly and Incorrectly

Post scores (% correct)	CC Table init. corr. (n=16)	CI Table init. incorr. (n=21)
1) TABLE	100	86
2) GOAT		
Existence	100	86
Equality	100	76
3) RUNNER		
Existence	100	86
Equality	94	67
4) TWO BOXES		
Existence	100	81
Equality	19	14
5) STEEL BLOCKS		
Existence	100	86
Equality	88	52

Table 17

Comparison of Student Ratings:
Control Explanation Given to Students
Initially Answering Table Problem Correctly and Incorrectly

	CC Table init. corr. (n=16)	CI Table init. incorr. (n=21)	
Average ratings			
1) TABLE			
Confidence	2.88	1.87	**
Sense	4.56	3.70	**
2) GOAT			
Existence (confidence)	2.79	1.93	*
Equality (confidence)	2.66	.51	*
Average confidence ratings			
3) RUNNER			
Existence	2.79	1.63	**
Equality	1.96	.46	
4) TWO BOXES			
Existence	2.72	1.37	**
Equality	-1.77	-1.09	
5) STEEL BLOCKS			
Existence	2.73	1.59	**
Equality	1.34	.32	
Student ratings of explanations			
Understandable and believable?	4.38	3.65	*
Helps to make sense?	4.63	3.62	**

* $p < .05$
** $p < .01$

Table 18

Comparison of Overall Performance:
Experimental Explanation Given to Students
Initially Answering Table Problem Correctly and Incorrectly

Post scores (% correct)	BEC Table init. corr. (n=33)	BEI Table init. incorr. (n=40)
1) TABLE	97	93
2) GOAT		
Existence	100	88
Equality	73	68
3) RUNNER		
Existence	97	90
Equality	67	64
4) TWO BOXES		
Existence	97	85
Equality	42	51
5) STEEL BLOCKS		
Existence	100	90
Equality	70	45

Table 19

Comparison of Student Ratings:
Experimental Explanation Given to Students
Initially Answering Table Problem Correctly and Incorrectly

	BEC Table init. corr. (n=33)	BEI Table init. incorr. (n=40)
<u>Average ratings</u>		
1) TABLE		
Confidence	2.77	2.43
Sense	4.53	4.36
2) GOAT		
Existence (confidence)	2.30	2.00
Equality (confidence)	.48	.65
<u>Average confidence ratings</u>		
3) RUNNER		
Existence	2.11	1.93
Equality	.38	.33
4) TWO BOXES		
Existence	2.08	1.76
Equality	.25	.46
5) STEEL BLOCKS		
Existence	2.09	1.90
Equality	.88	-.53 *
<u>Student ratings of explanations</u>		
Understandable and believable?	4.12	4.20
Helps to make sense?	4.21	4.43

* $p < .05$

Table 20

Comparison of Students' Average Sense Ratings of Control Examples: Students Initially Answering Table Problem Correctly and Incorrectly

	CC Table initially correct (n=16)	CI Table initially incorrect (n=21)
Athlete running	4.00	2.86 **
Finger on stone	4.31	2.76 **
Rowboat	4.50	3.62 **
Car	4.13	3.30 *
Gun firing	4.25	3.52 *
Balloon	4.44	3.90 *
Apple	2.69	2.67
All examples together	4.05	3.23 ***

* $p < .05$
** $p < .01$
*** $p < .0001$

Table 21

Comparison Of Students' Average Sense Ratings of Experimental Examples: Students Initially Answering Table Problem Correctly and Incorrectly

	BEC Table initially correct (n=33)	BEI Table initially incorrect (n=40)
Hand on spring	4.42	4.65
Book on spring (existence)	4.24	4.45
Book on spring (equality)	4.33	4.40
Book on board	4.13	3.97
Book on foam rubber	4.30	4.00
All examples together	4.29	4.30

Table 22

Comparison of Overall Performance:
Control Versus Both Experimental Explanations
(Students Initially Answering Table Problem Correctly)

Post scores (% correct)	CC Control (n=16)	BEC Experimental (n=33)
1) TABLE	100	97
2) GOAT		
Existence	100	100
Equality	100	73
3) RUNNER		
Existence	100	97
Equality	94	67
4) TWO BOXES		
Existence	100	97
Equality	19	42
5) STEEL BLOCKS		
Existence	100	100
Equality	88	70

Table 23

Comparison of Student Ratings:
Control Versus Both Experimental Explanations
(Students Initially Answering Table Problem Correctly)

	CC Control (n=16)	BEC Experimental (n=33)
Average ratings		
1) TABLE		
Confidence	2.88	2.73
Sense	4.56	4.53
2) GOAT		
Existence (confidence)	2.79	2.49
Equality (confidence)	2.66	.96
Average confidence ratings		
3) RUNNER		
Existence	2.79	2.37
Equality	1.96	.69
4) TWO BOXES		
Existence	2.72	2.27
Equality	-1.77	-.21
5) STEEL BLOCKS		
Existence	2.73	2.34
Equality	1.34	.79
Student ratings of explanations		
Understandable and believable?	4.38	4.12
Helps to make sense?	4.63	4.21

* $p < .05$

understanding. By contrast, about half of the experimental students answered this part of the two boxes problem correctly.

Although there was not a significant difference in overall performance on the post table problem, the experimental group had significantly higher average sense and confidence ratings (pre-post differences) for this problem. This group also gave the experimental explanation significantly higher ratings on how understandable and believable the explanation was and how much the explanation helped the idea of an upward force from the table make sense. Thus, although the student performance was not as strikingly different as it was in the interviewing study, there is evidence to indicate that the experimental explanation had a greater impact on students' conceptions than the control explanation.

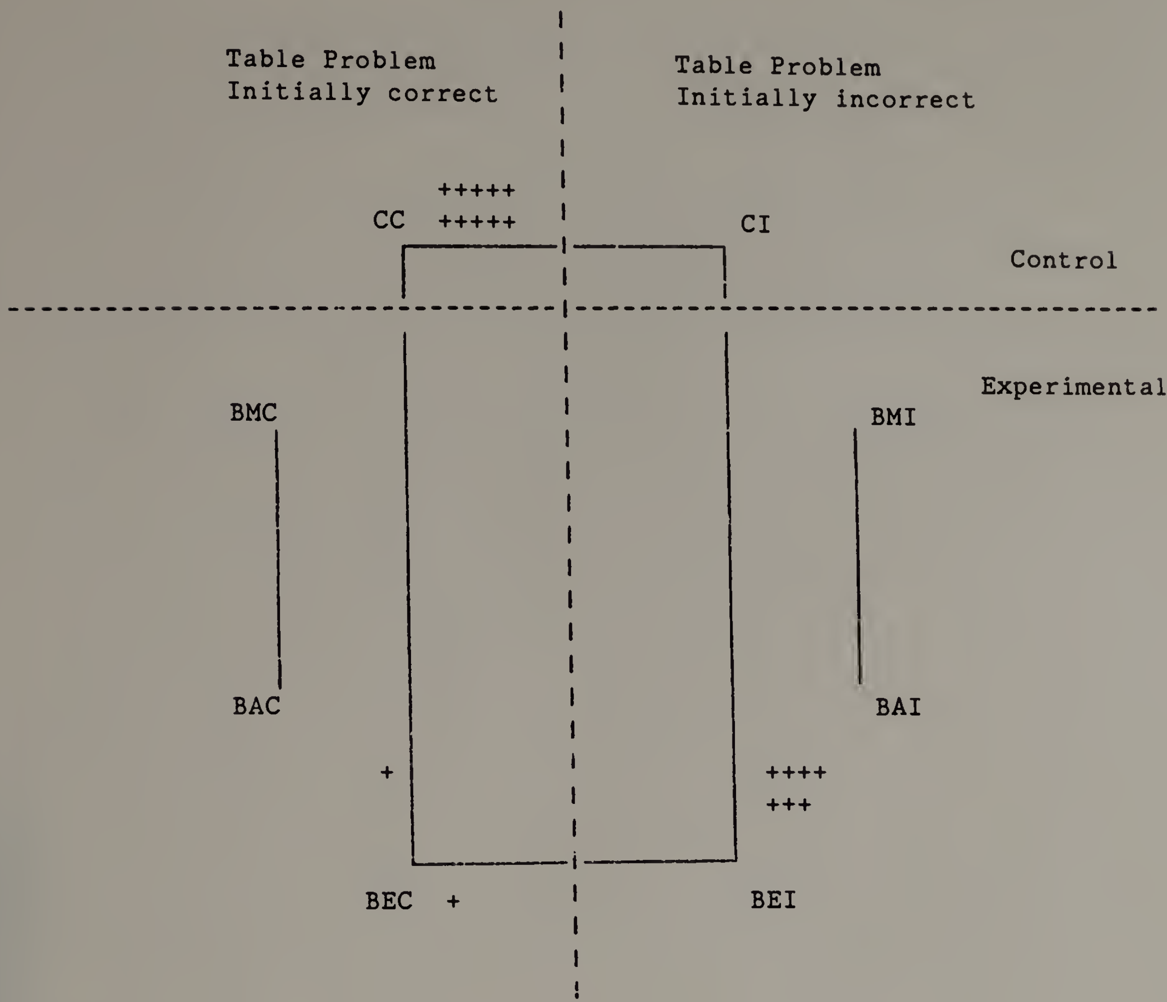
Another interesting difference emerged between the experimental explanation and the control explanation on comparing the control explanation with students initially answering the table problem correctly and incorrectly (CC with CI, tables 16 and 17) and the experimental explanation with students initially answering the table problem correctly and incorrectly (BEC with BEI, tables 18 and 19). Please note that in tables involving students who initially answered correctly, all comparisons are between post scores with no pre-post differences compared.

In the comparison of CC with CI, many significant differences emerged in favor of CC, whereas in the comparison of BEC with BEI, only one significant difference emerged in favor of BEC. It is especially interesting to note that students' sense ratings of the examples in the

explanations differed significantly between CC and CI in favor of CC, and the overall difference was highly significant, but there were no significant differences between the sense ratings of the examples in BEI and BEC (see tables 20 and 21). Thus it appears that the students' initial answer on the table problem significantly affected their sense ratings and confidence scores on their answers when they interacted with the control explanation, but not when they interacted with the experimental explanation.

Although the CC group performed quite well on the post questions (with the exception of the second part of the two boxes problem) and their scores were consistently higher than those of the BEC group, there were no significant differences in the pairwise comparisons between these two groups on post questions or ratings (see tables 22 and 23). However, the average sense rating of the examples in the explanations was significantly higher for BEC (4.29 vs. 4.05, $P < .05$). The above comparisons are summarized in figure 7. In this diagram, a plus (+) was placed near the the group which scored a significantly higher pairwise comparison along the line indicating the comparison. A plus was also included if the difference in the overall sense rating of examples in the explanations was significant. As can be seen in this diagram, the two comparisons which had a large number of significant differences both involved CI, an indication that the control explanation was comparatively ineffective when the students had a misconception about forces from static objects.

SUMMARY OF RESULTS OF COMPARISONS MADE: WRITTEN INSTRUMENT STUDY
(One plus given for each significant difference in the comparison)



LEGEND

CI Control, table problem initially incorrect
BMI Bridging plus model, table problem initially incorrect
BAI Bridging alone, table problem initially incorrect
BEI Both experimental together, table problem initially incorrect
CC Control, table problem initially correct
BMC Bridging plus model, table problem initially correct
BAC Bridging alone, table problem initially correct
BEC Both experimental together, table problem initially correct

Figure 7

Summary of Results of Comparisons

Results of the Qualitative Analysis

Reasons for Answering on the Pre Table Question

In addition to the numerical scores, students were requested to give written reasons for their answers on the pre and post book on the table problems and to answer questions after most paragraphs in the explanations. These written responses allowed a closer examination of students' reasoning and interaction with the explanations. On the pre book on the table problem, the students had a variety of reasons for answering that the table does not exert a force, but virtually all of the students answering that the table would exert a force gave a similar reason. Some examples of the various reasons are given below, starting with reasons students gave who answered the table would not exert a force.

A) The table has no agency for exerting a force (11 students):

(S1) The table is an inanimate object and thus couldn't exert a force on the book. Therefore, gravity pulls on the book holding it on the table.

(S37) The table doesn't exert force because there is no energy pushing up. There is no leverage.

(S56) The table needs energy to exert force. It doesn't have any. The book is exerting force using gravity as its energy.

B) The table is just in the way acting as a support (6 students):

(S5) The book is pushing downward. The table is immobile, just standing there.

(S21) The table is stationary. It is not pushing up, it is just blocking the path of the book to the ground.

C) The book would move up if the table exerted a force (5 students):

(S18) If the table were exerting a force up on the book, the book would be pushed or forced up. It wouldn't rest on the table.

(S48) The table does not exert an upward force on the book because of gravity. Gravity is the reason why the book is lying on the table, the book would be floating above the table if the table exerted force.

D) Because of gravity there is no upward force (26 students):

(S15) I DON'T think the table exerts a force up on the book. If anything, the book is using force. Since gravity is pulling both objects to the ground.

(S32) Because gravity is pulling everything down, therefore it's impossible for a force (under reasonable conditions) to be going up.

(S44) It is the book which is exerting a force on the table. Gravity is pushing (pulling) the book flat. The table is simply an extension of the ground, acting as a stopping place for gravity.

(S59) Both objects are being forced down by gravity. The table merely supports the book.

E) The book is just resting there (2 students):

(S19) The book is resting on the table and not applying any force on the table.

F) The table is not pushing or pulling (7 students)

(S8) If force is a push or a pull, then I don't think the table is a part of force in this example.

There were 4 other students whose answers were not able to be classified together. As can be seen, the general concept of gravity figured heavily in many students' answers. Even students whose answers were classified under other categories frequently mentioned gravity. Perhaps since the goat problem involved horizontal forces, and thus gravity would figure in much less, the error rate on the existence part of the pre goat problem was lower than that of the pre table problem, with 55% answering the table problem incorrectly and only 45% answering the goat problem incorrectly. In the original tutoring interview study described in the background section, when asked for examples of force, every student gave gravity as one of their examples. This force seems to be, for most students, the prototypical agency for force in the physical world. For many students the fact that this force is directed downward seems to preclude an upward force from an object which is not also an agency for force.

Unlike the answers of the students initially responding incorrectly to the table problem, the answers of those who responded correctly fell largely under one category, indirect causal reasoning, that is, saying the table must have a force without explicating an agency for the force. This could be broken up into three subcategories: 1) if the table didn't exert a force, the book would fall (or the table would break), 2) the table has to exert a force to compensate for the downward force of the book, and 3) the table is holding the book up. Examples of these three subcategories are given below.

A) An effect not observed would occur if there were no force (29 students)

(S62) If the table didn't exert a force on the book, the book would hit the floor.

(S76) If the table did not exert an force that was the same as the force the book is exerting, the book would knock the table over.

(S79) The table exerts a force on the book because if there wasn't any force present then the book would fall to the floor. An example would be using a piece of paper to hold the weight of a heavier book.

(S88) If the table didn't exert a force upward, then the book would be able to break the table in half and fall to the floor.

B) The table must exert force to compensate for the weight of the book due to gravity (6 students)

(S78) The force of the book resting on the table is pushing against the force that is on the table.

(S102) It's like the wall and the goat, if one object is exerting force, the other object must exert an equal amount of force to maintain the stalemate.

C) The table is holding the book (6 students)

(S98) The table has to hold the book up. To hold anything up you need force.

(S105) The table does exert a force on the book because it is pushing it upward and suspending it using force.

There were 8 other students whose answers were not able to be categorized together (e.g. "I don't know" and "It has something to do with forces and gravity"). Of all the students, there was only one who mentioned an agency for the force, in this case, friction.

(S80) Because must balance out. Friction between book and table causes force (push & pull on object).

The overwhelming impression from these student comments is that virtually none of them explicitly considered where the force from the table could come from. For the majority of students, this meant that the table could not exert a force. But quite a few seemed willing to ignore this because the table must be exerting a force to balance the downward force of the book and keep it from falling and/or breaking the table.

Responses to the Questions in the Control Explanation

Except for the first question in the control explanation, which asked "Can you state Newton's third law in your own words?" the questions in the control explanation asking for written student response were all of the form "Can you say in your own words what this paragraph is trying to argue?" In general student response to these questions was quite dutiful and unenlightening. Some examples follow.

The question after the first paragraph asked students to state Newton's third law in their own words.

(S2) If one object creates a force on another, then, therefore, the other object creates an equal force.

(S8) If there is an object projecting a force to another object then the other object is giving a force back.

The second paragraph introduced the example of an athlete running

saying that her action of pushing back on the ground also involved a push of the ground forward on her. There was no question after this short paragraph as the third paragraph expanded on this example by discussing force as an interaction, saying that action and reaction coexist, that one does not cause the other, and that you cannot have one without the other. The question asked students to say in their own words what the paragraph was trying to argue.

(S3) It's saying reaction, and action are impossible without each other. They really go with each other.

(S8) This paragraph is saying that an action and a reaction cannot exist without the other, even though they do not follow each other.

The fourth paragraph introduced the example of the finger pressing on the stone and stressed that the equal and opposite forces happen on two different objects. Again the students were asked to say in their own words what the paragraph was trying to argue.

(S2) If one pull or push force occurs then at the same time, the other object gives a similar pull or push that is equal.

(S5) Force reactions are opposite but equal.

The fifth paragraph introduced the examples of the rowboat and the car, which are set in motion by the push of the water on the oars and the ground on the tires. Again the students were asked to say in their own words what the paragraph was trying to argue.

(S6) To make something go, there has to be 2 forces.

(S7) Newton's Law has many common examples backing it up.

The sixth paragraph introduced the examples of the rifle, the balloon and the apple falling to the earth pulling the earth up in return. Again the students were asked to say in their own words what the paragraph was trying to argue.

(S2) If a movement goes forward or backwards, then there is an a force going in the opposite direction also.

(S4) There is an opposite force pulling or pushing the same as the first. This sets objects in motion.

Although the responses in general indicated an ability to extract some amount of meaning from the paragraphs, they left one with the impression that the students may have been largely interacting with the text at a rather superficial level rather than thoughtfully considering the implications of the explanation. This was in stark contrast to the generally very thoughtful consideration of the control explanation by the students in the interviewing study.

Responses to the Questions in the Experimental Explanation

Analogy Relations Indicated by Written Student Responses

By contrast, student responses to the questions during the experimental explanation were varied and interesting and seemed to indicate genuinely independent and thoughtful consideration. All but two of the questions asked the students to indicate whether they believed the situation under consideration was different than the book on the table situation. The students' responses to these questions

were put into one of four categories: 1) the student felt the situations were analogous, 2) the student felt the situations were not analogous, 3) the student was undecided, and 4) their belief about the analogical relatedness could not be determined from their answer. Each of these categories is illustrated below by one example from each of the four times the question was asked, for the situations of the hand on the spring, the book on the spring, the book on the flexible board, and the book on the foam rubber. (Note: Remember that the question asked if the student thought the following situations were <u>different</u> from the book on the table situation.)

1) The situations are analogous

The hand on the spring:

(S36) No. I get it now. If you push an object that weighed 1,000 pounds on the table, the table would not longer have the force needed to support the object.

The book on the spring:

(S32) No, I realize now that is might be possible that you need force working both ways to keep an object stable.

The book on the board:

(S28) No, they are both wood and a little flexible.

The book on the foam rubber:

(S34) No, both compress under the book's weight. Both exert force.

2) The situations are not analogous

The hand on the spring:

(S24) Yes. When you put your hand on the spring and push it down, into an unnatural position, its natural position is a relaxed coil. If you push it down, you're making it fight against you. When you apply pressure to the table, it is not in an unnatural position, it's not fighting against the book.

The book on the spring:

(S23) Yes, the spring gives to even out the weight of the book by pushing back the same weight as the book. The table just can withstand a certain amount of weight.

The book on the board:

(S40) Yes. The book on the board is much different than the book on the table. The table is hard.

The book on the foam rubber:

(S31) It seems the foam rubber would be exerting force and the table not. Because the foam is soft, and it will bounce back like the spring and board.

3) The student was undecided

No students fell in this category for the hand on the spring situation.

The book on the spring:

(S50) It's beginning to look like the same situation, yet it's hard to understand.

The book on the board:

(S53) A little bit, but pretty close.

No students fell in this category for the book on the foam rubber situation.

Table 24 shows the percentage of students answering in each of the above categories for each of the four situations compared with the book

on the table. With the exception of a slight rise in percentage of students categorized as answering that the book on the foam situation is not analogous to the book on the table, the percentage of students indicating the situations were not analogous dropped consistently and the percentage of students indicating they were analogous rose consistently.

This trend is mirrored by the number of students answering the running table problem asked quickly at the end of each paragraph without a confidence rating. As figures 8 and 9 show, there was a fairly steady rise in the number of students indicating the table exerts a force as the explanation proceeded. This is in sharp contrast to the shape of the graph in figure 11 for the control explanation which rose quickly after the first paragraph and stayed almost level for the rest of the explanation. It is interesting to note, looking at figure 10 which shows the combined responses of the two experimental explanations, that the sharpest increases came after the paragraph with the example of the book on the hand explicating the indirect causal argument, and the paragraph talking about the microscopic perspective (the experimental explanation without the molecular model still discussed the microscopic nature of the table's springiness).

Because each student was asked to indicate both whether they saw the example situations as different than the book on the table situation as well as indicating their running answer to the book on the table question, it is possible to examine the correlations between their indications of analogical relatedness and their answers to the running book on the table question. One would expect that most

Table 24

Percentage of Students Indicating the Book on the Table Situation is Analogous to the Example Situations in the Experimental Explanation

	Table initially incorrect				Table init. correct
	Hand on Spring	Book on Spring	Book on Board	Book on Foam	Hand on Spring
Not analogous	85%	58%	28%	38%	33%
Analogous	8	28	50	50	27
Undecided	0	8	13	0	30
Answer unclear	8	8	10	13	9

Table 25

Correlations of Student Indications of Analogical Relatedness with Their Running Answers to the Book on the Table Problem

		Does the table exert a force?	
		Yes	No
Situation different than book on table?	No	52	2
	Yes	12	71

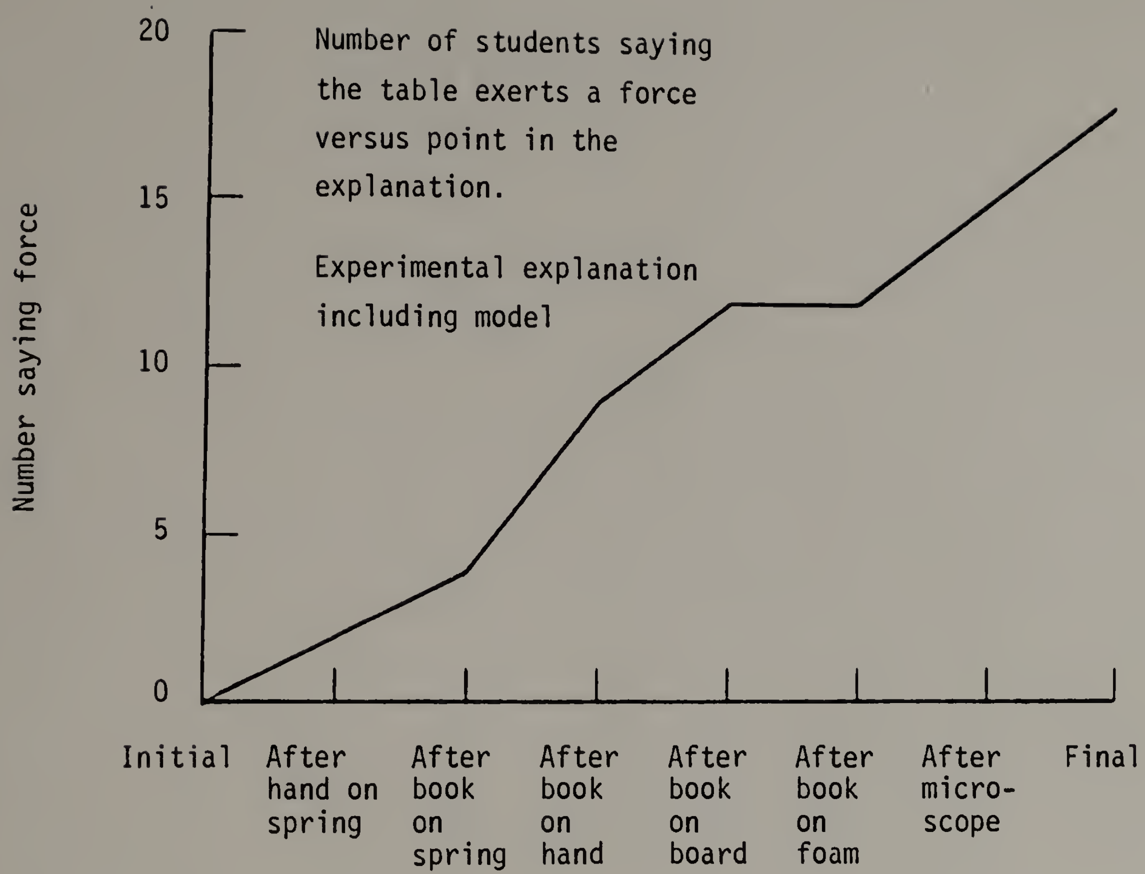


Figure 8

When Bridging Plus Model Students Accepted Force

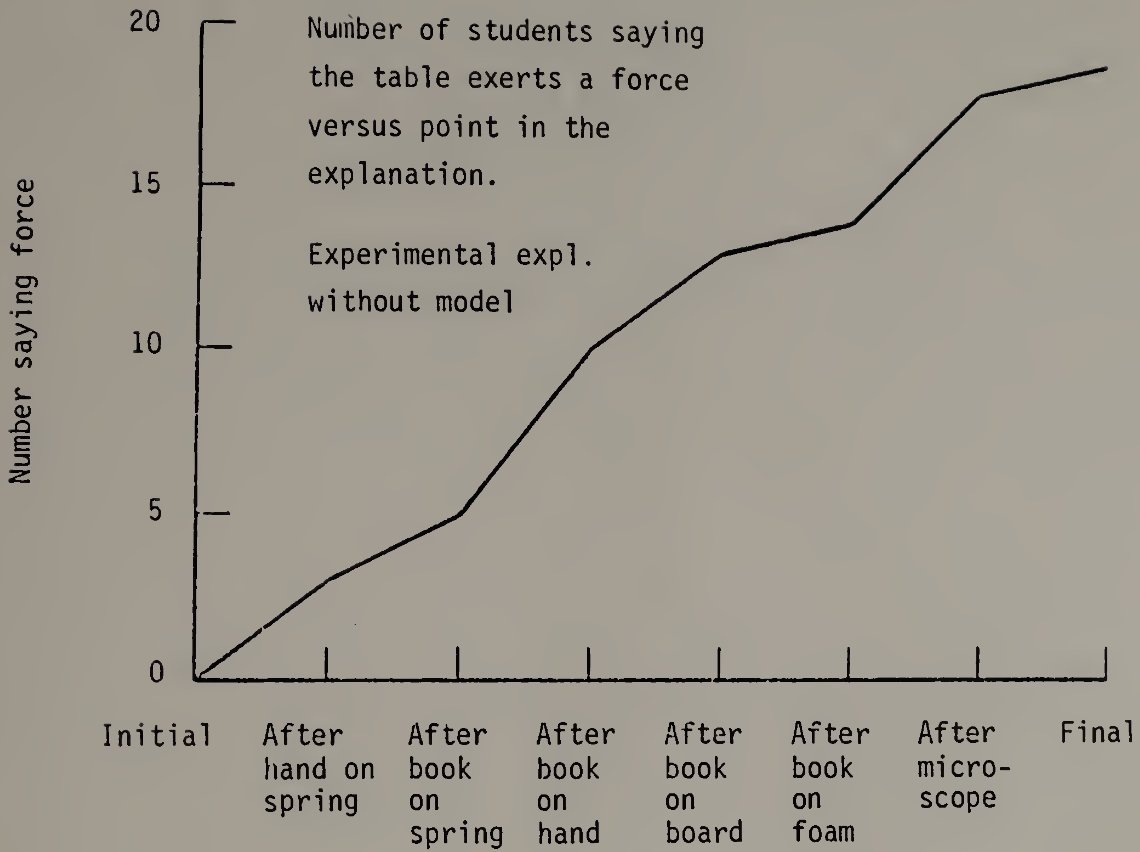


Figure 9

When Bridging Alone Students Accepted Force

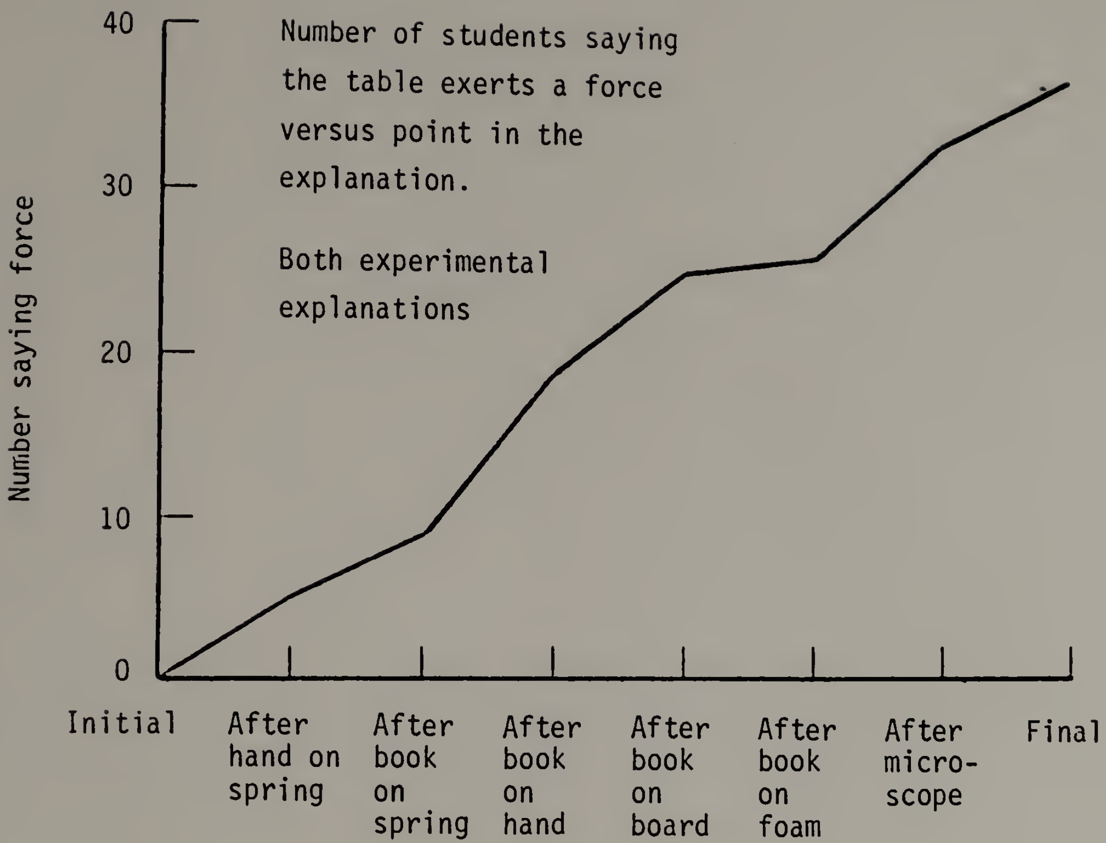


Figure 10

When Both Experimental Groups Accepted Force

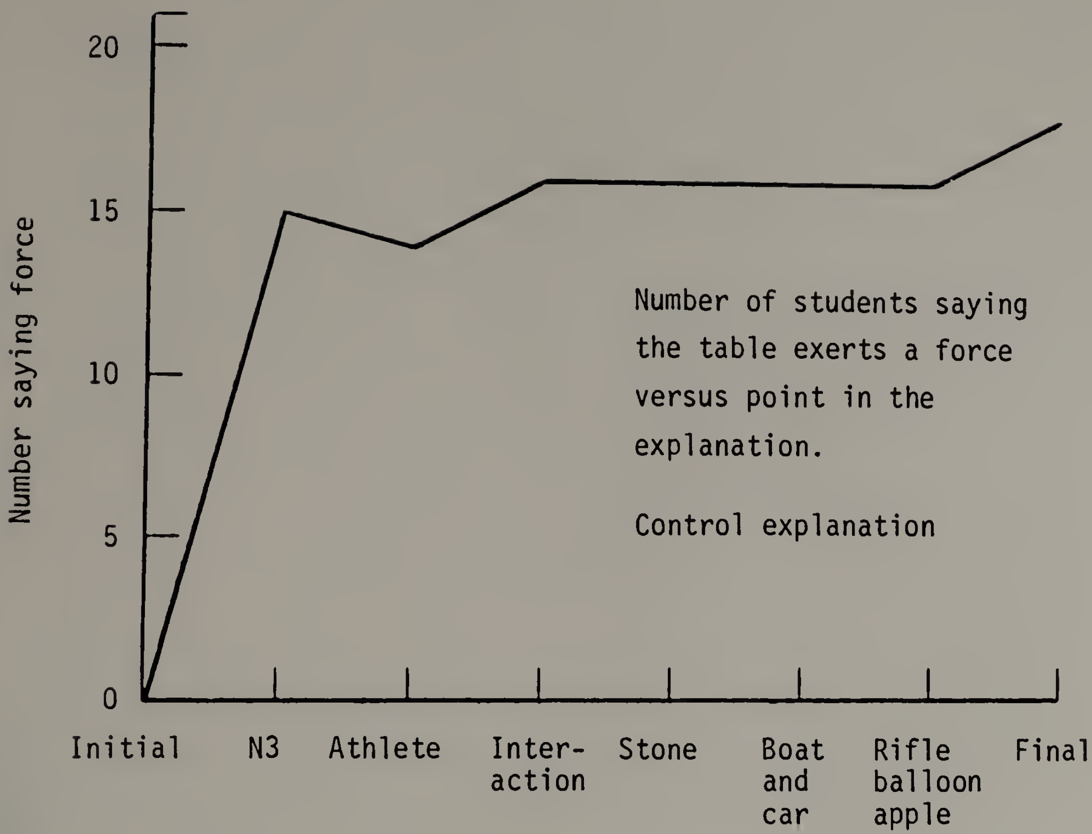


Figure 11

When Control Students Accepted Force

students who answered that the situations were analogous (i.e. were not different) would give the same answer for the book on the table situation as for the example situation, and if they indicated that they saw them as different, that they would answer differently.

Table 25 shows a correlation of the students' indication of analogical relatedness (between the four situations and the book on the table situation) and their answers after each paragraph about whether the table exerts an upward force. For example, there were 52 responses (across all four situations in the explanation) categorized as indicating that the student viewed the situation under consideration as analogous with the book on the table situation and after which the student answered that the table exerts an upward force.

The two responses shown in the upper right corner of table 25 show responses in which the student indicated that she thought the situations were analogous, but then answered that the table does not exert an upward force. However, both answers were given by the same student, and even though she said the situations were analogous and went on to say the table does not exert an upward force, in her explanation she made it clear that this was because she believed there was no upward force in the situations in the explanation either. Thus there was not a single instance of a student indicating analogical relatedness who answered differently for the two situations. By contrast, there were 12 instances of students saying the situations were not analogous yet indicating directly afterwards that the table exerts an upward force.

Also, as shown in table 24, 33% of the students initially answering the table problem correctly (11 students) indicated they believed the book on the table situation was not analogous to the hand on the spring. Although it is possible these students all believed the spring does not exert an upward force on the hand, this is unlikely from their written responses, from prior data indicating well over 90% of students believe the spring exerts an upward force on a hand, and from these students' high sense ratings that the spring exerts an upward force. It would appear from this that perception of analogical relatedness is a sufficient, but not a necessary, condition to ensure similar answers.

Another interesting result emerged from examining student response to the question about analogical relatedness after the third paragraph in the experimental explanation in which the indirect causal argument was given for the book on the spring and the book on the hand. After this paragraph, 23 people indicated that they believed the book on the spring was not analogous to the book on the table, and 11 indicated they they believed there was an analogy relation. Of the 11 who said the situations were analogous, only one indicated that the table would also be flexible. The other 10 indicated only that the table would also need to exert a force to balance the downward force of the book. These 10 students apparently considered the table as <u>like</u> a spring in that it would also exert force upward, but they did not consider the table <u>as being</u> a spring. This distinction in types of analogical relatedness is developed further in the general discussion chapter.

Of the 23 students who indicated the situations were not analogous, 17 said so because they saw the table as not being

compressible (or not having another source of agency such as motion or volition). However, by the end of the explanation, when asked whether the table was deformable or springy, only two of the forty students receiving one of the experimental explanations clearly indicated it was not, while 34 clearly indicated that they thought it was springy. Thus it appears that the great majority of students underwent a change in their concept of the table from the table as a rigid object to the table as a kind of spring.

Reasons for Answering on Post Table Question

This new view of the table as springy was reflected in the students' reasons given on the post table problem. Twenty two of the forty students who received one of the experimental explanations gave as their reason for this problem that the table is springy or compressible (eleven from each of the two experimental explanations). Six of the eleven students who had received the bridging plus model explanation mentioned the molecular model. Four experimental students gave an indirect causal reason (the table pushes so the book doesn't fall or the table break), one student said the table wanted to get back to its original shape, three students answered the post question incorrectly, and the remaining ten students gave non-reasons such as "I think the table exerts force to equal that of the book." Some examples from each of these categories are given below.

The table is springy

(S29) The table does exert a force on the book because the table has a slight "springiness" and it would rather be totally straight.

(S44) Everything, as fixed or rigid as it may seem, has a springy tendency. It absorbs force and repels force (I think). It counter-exerts a force upward on the book.

(S60) The table has a springiness so that, when compressed, it will push backwards.

The table has springy molecular bonds

(S30) The table contains molecules which are springy therefore it does exert force up on the book.

(S38) Because it is made up of molecules with springy bonds which compress and create an upward force.

Indirect causal argument

(S46) It exerts force because in able to hold it up, it must return the same amount of force as the book has, otherwise it will fail.

(S56) To hold the book, the table must equal the force that the book is pushing down with by pushing up.

Student gave incorrect answer

(S40) There is no force on the book at all.

(S59) It has supported itself and the book.

Of the twenty students who received the control explanation, twelve gave as a reason either a paraphrase of Newton's third law or simply the statement, "because of Newton's third law." Two students gave an indirect causal reason, three answered incorrectly, and the remaining five gave non-reasons. It is interesting that all three of the students who answered incorrectly mentioned gravity or weight as important to their reasoning. Examples of each of these categories follow.

Newton's third law

(S4) It does because there is an equal and opposite force between 2 objects.

(S12) Newton's Third Law: For every force, there is an equal opposite.

Indirect causal

(S2) It exerts a force because if there is one force there is always another force of equal magnitude occurring to balance it.

Student gave incorrect answer

(S10) The book is the only thing that exerts a force, because of its weight.

(S15) Contrary to Newton's Third Law, I still think gravity will have an effect.

(S17) Because the force of gravity makes the book push down upon the table.

Conclusions

Even though the comparative performance on post questions between the experimental and control groups (students initially answering the table problem incorrectly) was not as strikingly different as in the interviewing study, there were some definite indications that the experimental explanation was more effective than the control explanation. First, the students interacting with the experimental explanation rated it significantly higher than the students interacting with the control explanation on the two questions of how understandable and believable the explanation was and how much the explanation helped the idea of an upward force from the table make sense.

Second, although most students in each group answered the post table problem correctly, the pre-post differences in confidence and sense ratings were significantly higher in the experimental group. Third, the experimental group's performance on the two boxes problem was strikingly and significantly superior, as only 14% of the control students answered this problem completely correctly compared with 51% of the experimental students. This non-example problem was included to test whether students were answering based simply on a memorized principle with little deeper understanding. It appears that most of the control group subjects fell into this category, while many of the experimental group subjects were apparently able to reason more flexibly about forces on this problem.

Fourth, student response to the control explanation was dependent on their initial answer to the book on the table problem. Students' confidence ratings on the post questions and their sense ratings of the examples in the explanation were significantly lower when the student had answered the table problem incorrectly. By contrast, answering the table problem correctly or incorrectly seemed to have little effect on students' high sense ratings of the experimental explanation examples or their performance or confidence ratings on the post questions. This raises the hypothesis that students with a preconception were impeded in their interaction with the control explanation, whereas the experimental explanation engaged intuitions which were common to all students regardless of their prior conceptions concerning forces from static objects.

Finally, one received the general impression from the homogeneity of students' responses to the questions during the control explanation that their interaction with the explanation was dutiful but somewhat superficial. By contrast, the variety of student responses given to the questions in the experimental explanation gave the impression of students engaged and interacting thoughtfully with the explanation.

In addition to the comparison between the experimental and control explanations, the data provided an interesting look at students' interaction with the experimental explanation. As shown in figure 10, students' running answers to the book on the table problem gave a picture of students gradually coming to a realization that the table exerts a force as the intermediate analogies more nearly bridged the gap between students' conceptions of the table and students' conceptions of the spring. This is an indication that a single analogy would simply not have been effective for most of the students, an interpretation supported by students' indications of analogical relatedness of the situations to the book on the table situation which showed a roughly steady increase throughout the explanation.

Not a single student gave an answer which was coded as indicating that they believed the situation in the experimental explanation to be analogous to the book on the table situation and then gave an answer different from the answer they gave for the book on the table situation. This would seem to indicate that an analogical connection to an anchor is a sufficient condition for change. However, it does not appear to be a necessary condition as 12 of the 83 students whose answers were coded as indicating they felt the situations were not

analogous gave the same answer for the two situations. Thus it appears that if an anchor is viewed as analogous to a problem situation, this is sufficient for change, but this perceived analogical relationship is not absolutely <u>necessary</u> (although it appears to be quite <u>important</u> as the great majority of students answering correctly the ongoing table question indicated that they considered the situations analogous).

These results indicate that a perceived analogy relation implies (in the strong sense) that the student will give the same answer for the two situations. Another way of stating this is that students appear to consider a perceived analogical relationship as proof positive that the situations will be equivalent in relevant dimensions. This indicates that the use of analogies in the classroom can be a powerful tool for inducing conceptual conflict if students can be brought to see two situations as analogous for which they previously held conflicting beliefs in a relevant dimension. The use of bridging analogies appears to be one way of establishing such analogy relations.

The data also seemed to indicate that the great majority of students interacting with the experimental explanation changed their concept of a table as a rigid object to that of the table as a kind of spring. However, some students during the explanation viewed the table as analogous to a spring without appearing to view the table as springy in any way. The analogy relation seemed to be based simply on the fact that both objects would exert an upward force when a downward force was exerted on them to maintain a kind of balance or equilibrium. This raises the question of different types of analogical relatedness, a situation viewed as being <u>like</u> another situation (the table is like a

spring in that both push up) versus a situation viewed as being another situation (the table is a kind of spring).

CHAPTER VI

GENERAL DISCUSSION

The original purposes for the studies were twofold: first, to explore whether students' consideration of thought situations alone (i.e. without additional empirical experiences) can have an impact on their misconceptions; and second, to examine whether different methods of using thought situations have different effects on students' misconceptions and the reasons for these differences if any exist. While examining the data, in addition to providing partial answers to these questions, some issues were raised which inspired further hypotheses and may provide direction for future research. In the following two sections these partial answers and hypotheses will be further examined.

General Conclusions From the Data

In the following two sections I will discuss conclusions from the data of both of the current studies in light of the research questions.

Research Question One

1) Can thought situations alone bring about conscious conceptual change?

In an effort to veer away from a purely formal presentation of the material, in recognition of the principle that personal involvement is important to learning, and in keeping with the scientific principle of empirical verification rather than reference to authority, in recent years science educators have advocated a great deal of hands-on laboratory experience in science courses. However, in some cases there is a tendency to expose the student to more and more experiences which are often meaningless to him or her (or meaningful in inappropriate ways), and do little to increase conceptual understanding.

In some cases, the philosophy guiding the increase of laboratory experience is that if the student can have experiences in closely controlled environments where many irrelevant or confusing variables (e.g. friction) are eliminated, the concepts will become clear. However, such laboratory experiences may fail to make concepts clear for at least two reasons: 1) students are often not aware what variables have been controlled, and if so why, and 2) students will tend to interpret the experiences using their naive conceptual frameworks and often see only what they expect to see. Added to these problems is the opaqueness of many lab procedures - the important concepts are buried in a mass of calculations and graphical manipulations, many of which the students do not understand. The immediacy necessary for even a start at overcoming misconceptions is often completely absent.

Although hands-on labs are pedagogically desirable and necessary, students may often need help in interpreting laboratory experiences as

well as the great amount of empirical experience they have had outside of the classroom. To do this, a well focused combination of laboratory experiences and rational discussion about "real life" and laboratory experiences may be required. In these studies, I have attempted to take a close look at two particular types of rational discussion about a particular situation, that of a book resting on a table. Neither of these types of discussion involved further empirical experience but rather asked students to think about concrete physical situations which were either familiar or easily imagined, such as an athlete running or a hand pressing down on a spring.

It would be difficult to give a conclusive answer to the question of whether thought situations alone can bring about conceptual change in some domains for some students given the elusiveness of a firm operational definition of conceptual change. However, there were indications from several sources in these studies that the experimental explanation succeeded in changing the students' conscious conceptual frameworks. First, in virtually every case (94%) in which a student initially answered the table problem incorrectly and then interacted with the experimental explanation, the student changed to the correct answer and indicated that she was confident about this answer and that this answer made sense to her.

Second, in both studies, performance of the students interacting with the experimental explanation on transfer questions was encouraging. In particular, performance on one of the transfer questions (the Two Boxes Problem) was quite encouraging. This was a non-example in that the forces to be compared are not equal. This

question was included to identify students who answered the questions based only on a memorized rule such as "forces always equal and opposite" with no deeper understanding. Six of the seven students who initially answered the table problem incorrectly in the interviewing study answered this problem completely correctly, and over half of the experimental students initially answering the table problem incorrectly in the written instrument study answered correctly.

Finally, and perhaps most importantly, the experimental students' reasons for their answers to the post questions in the interviewing study (in particular their answers to the steel blocks problem) showed that in general they were reasoning about force as an interaction between two objects rather than force as an innate or acquired property of objects, even though most mentioned considering the concept of force as a property. This is an indication that the students had been given a way of thinking about force which enabled them to veer away from the seductive conception of force as a property and toward a more sophisticated interaction conception. Thus the data from this study are quite consistent with and supportive of the hypothesis that in certain situations, thought situations alone can bring about conceptual change with no further empirical experience.

Research Question Two

2) For the two explanations examined in this study, does the explanation which uses bridging from a thought situation anchor to establish a causal model increase student performance more or less than

the explanation making use of concrete examples inductively supporting and illustrating a stated principle?

Gick and Holyoak (1983) report a study in which they conclude that a person presented with multiple analogies induces an abstract schema which aids consideration of analogous situations. However, Kaiser, Jonides, and Alexander (1986) describe a study very similar to Gick and Holyoak's in which they explored the effect of analogous problems presented before target problems. Unlike Gick and Holyoak, prior experience with one or two analogous problems had no effect on later performance on the target problem, the subsequent path of a ball that has been rolled through a curved tube, a problem which reveals misconceptions in many subjects (cf. McCloskey, Caramazza, and Green, 1980). The more familiar analogs, for which subjects more frequently answered correctly, were water coming out of a curved hose and a bullet out of a curved gun barrel. Apparently, when subjects hold a misconception about the target problem, schema induction may not be a good description of the effect of multiple analogies.

Indications from the Interviewing Study

This certainly appeared to be the case in the present interviewing study. When students were presented with multiple examples illustrating an abstract principle, most of the control students refused to accept a conclusion which they found counter-intuitive. In contrast, when students were presented with a sequence of bridging

analogies in the experimental explanation which explicitly illustrated the analogical connection between the book on the table (the target problem) and the hand on the spring (a conceptual anchor) by demonstrating similar underlying structure (springiness), the students in the interviewing study did not hesitate to accept the conclusion that a static object can exert a force. Student performance on other post questions in the interviewing study showed equally large discrepancies between the performance of the experimental and control groups in favor of the experimental explanation.

Not only were the numerical scores strikingly and significantly different, examination of students' reasons for their answers showed apparent differences in students' conceptions of force between the experimental and control groups after the students had interacted with the explanations. In the steel blocks problem, all three of the control students who answered correctly that the smaller bottom block would exert a force upward on the larger top block incorrectly answered that the larger top block would exert the larger force, giving as a reason that the larger top block has a greater force. This indicates a naive conception of force as a property of an object.

By contrast, only one of the seven experimental students who answered the first part of the question correctly (that the bottom block would exert an upward force) answered the second part incorrectly. The other six, although most indicated considering answering this part of the question based on a concept of force as a property of an object, answered correctly that the forces would be equal. One student (SE2) initially gave the correct answer but

indicated that this answer did not make complete sense to him because the upper block was so much bigger. However, after an impressive spontaneous connection to the situation of the book on the spring, the 40 pound lower block's being able to exert 200 pounds of force made complete sense to him, since the spring weighed less than the book but it was able to exert an upward force equal to the book's weight by virtue of its springiness. This spontaneous analogy provided a demonstration of the potential of the experimental explanation to help students reason more effectively about situations involving force. Thus, in the interviewing study, the indications seemed clear that the experimental explanation was superior in terms of its effect on student conceptions.

Indications from the Written Instrument Study

Although there were also indications in the written instrument study that the experimental explanation was superior, the fact that the results differed from those of the interviewing study (the majority of the students in the written instrument study accepted the conclusion of the control explanation) deserves some consideration. There are at least three possible reasons for this apparent difference in student reaction to the control explanation between the interviewing study and the written instrument study.

First, the two studies were conducted at two different schools. Second, the setting for the interviewing study was probably quite unique in the students' school experience, whereas the setting for the

written instrument study closely resembled the setting for a quiz or other in-class written work. This similarity to a typical school setting may have made the students less thoughtful than the interviewing students and more likely to settle into the "school survival" mode of latching on to any quick and easy way of getting the right answer (e.g. application of a memorized rule). That many of the control students held this attitude is supported by the homogeneity and apparent superficiality of the written responses the control students gave to the questions asked during the explanation.

Third, in the written instrument study students had to respond to the running book on the table question after each paragraph. The students interacting with the control explanation might have continued with their first answer (which for most students after the first paragraph was that the table exerts a force) just to be consistent, whereas if they had not needed to commit themselves all along, they might have rejected the conclusion of the explanation more often. In the interviews, several control students who seemed to reluctantly agree with the explanation at the beginning, and might have answered then that the table exerts a force, rejected the explanation later. Curt, the student in the control case study, was one such student. By contrast, most of the students in the experimental explanation did not answer the running table question correctly until well into the explanation and so this argument could not be applied to the experimental students.

Despite the fact that performance on the post table question was not significantly different between the control and experimental groups

in the written instrument study, students' ratings of how confident they were in their answer to this question and their rating of how much the answer made sense to them rose significantly more from the pre-question for those students interacting with the experimental explanation. There was also another important difference in student performance on the two boxes problem. This problem is a non-example in that the forces to be compared are not equal and was included to give trouble to students who were simply answering the questions with a memorized rule such as "forces always equal and opposite" without any deeper understanding. The fact that only 14% of the control students answered this problem correctly testifies to a relatively superficial level of understanding on the part of most of the control students.

Thus the results from both the interviewing and written instrument studies indicate that the experimental explanation resulted in superior performance on the post questions, and from the protocol data in the interviewing study, there is evidence indicating the experimental students gained a superior understanding of the concept of force. In the written instrument study a "school survival" mode of latching onto any quick and easy method of getting the correct answer (e.g. rote application of Newton's third law - forces always equal) would have served a student well on the post questions for all but the second part of the two boxes problem. On this crucial test of ability to flexibly reason about situations involving forces, 51% of the experimental students answered correctly compared to only 14% of the control students, thus providing another indication that the experimental students gained a superior understanding of the concept of force.

Research Question Three

3) When tutoring which uses thought situations works (i.e. has an effect on student misconceptions), why and how does it work? When it does not work, why does it not work?

It appears from the current studies that instruction which is grounded in students' physical intuition will be effective. This is certainly not a new insight - the idea that instruction must take into account existing student conceptions falls easily within a standard constructivist framework of instruction. In the study of student conceptions in science, this taking of student conceptions into account has largely meant simply the description of students' "incorrect" preconceptions. However, it appears that students may hold a number of "correct" preconceptions upon which instruction may be based. The experimental explanation, which was designed to draw on and extend existing student intuitions, appears from the data of the current studies to have been more effective than the control explanation which neither drew on nor extended existing "correct" student intuitions.

Examples Must Make Sense to the Students

That the experimental explanation drew on students' existing correct intuitions is evidenced by the students' consistently high sense ratings for the examples in the experimental explanation. In the

interviewing study, the average sense rating for all of the examples in the experimental explanation was 4.60 out of a possible 5, and the average rating for the conceptual anchor (the spring pushing upward on the hand) was 4.71. In the written instrument study, the average rating was a 4.30 and the average rating for the anchor was 4.65. By contrast, the average rating for the control examples in the interviewing study was only a 3.27 out of 5, with the idea that the ground presses forward on a runner rated on the average only 2.14. The average sense rating for the control examples in the written instrument study was 3.23, and the rating for the runner example was 2.86. These ratings indicate that the Newtonian concept of a reaction force was intuitively understood by most students for the situations presented in the experimental explanation but not for the situations presented in the control explanation.

Need to Develop Analogy Relations Explicitly

There is also evidence that the experimental explanation extended these intuitions. In both the interviewing and written instrument study, very few students who initially answered the book-on-the-table problem incorrectly indicated that they believed the hand-on-the-spring situation was analogous to the book-on-the-table situation, largely because they viewed the table as rigid. However, by the end of the experimental explanation, the great majority of the students in both studies indicated that they viewed the table as springy to some extent.

Thus there is evidence that the intuitive understanding of a conceptual anchor had been transferred to the target problem.

The indications from the data are quite strong that this transfer came largely as a result of students' interaction with the multiple intermediate analogies. From the number of spontaneous analogies and bridges in the interviewing study (10 spontaneous analogies, five of which were intermediate analogies or bridges) the students interacting with the experimental explanation displayed both a willingness and ability to reason analogically. From several of these students' retrospective comments, the development of analogical connections was important to them in their understanding that the table exerts a force. In the written instrument study, from their answers to the running question about the book on the table after each paragraph, students seemed to come to a gradual realization that the table exerts a force as they encountered more and more examples in the experimental explanation (see figures 10).

By contrast, the control explanation did not attempt to extend student intuitions by explicitly developing analogical relationships from examples which the students found understandable to the target situation of the book on the table. There were three control examples in particular which the students found reasonably understandable: the rowboat (interviewing average sense rating of 4.00, written instrument rating of 3.62), the rifle kick (interviewing rating of 4.14, written instrument rating of 3.52) and the balloon spurting out air (interviewing rating of 4.43, written instrument rating of 3.90). However, there was no attempt to relate these situations analogically

to the book on the table situation. Rather, these examples were simply discussed as separate illustrations of the application of an abstract principle, Newton's third law.

Kaiser, Jonides, and Alexander (1986) concluded that the reason for the lack of analogical transfer in their study on multiple analogies of objects emerging from curved tubes was due to the subjects' finding differences between the "analogous" situations, such as the speed and the substance of the issuing projectile. This seems to indicate that when a student has a misconception, it may not be an appropriate instructional strategy simply to present the student with multiple examples in hopes that he or she will induce an abstract concept from the examples. The Kaiser et al. study as well as the current studies suggest that some learning situations may require the explicit development of analogy relations between examples in addition to the simple presentation of the examples themselves.

Mechanistic Models are Important

In addition to the explicit development of an analogy relation between the conceptual anchor (the spring pushing up on the hand) and the target situation, the experimental explanation also provided a microscopic model of molecules connected by springy bonds. This model, in concert with the other examples, provided an agency for the force, the microscopic compression or bending of the table. In the interviewing study, a primary reason students rejected the conclusion of the control explanation was that it provided no indication of a

source for the force from the table. The experimental explanation provided a causal model for the table indicating the source of the force whereas the control explanation did not. This is discussed further in the following section which discusses findings related to the fourth research question.

Research Question Four

4) From the students' interactions with the thought situations in each of the explanations, what can be said about students' causal reasoning and use of causal models?

While interacting with the two explanations, students in the interviewing study gave quite a few indications of causal reasoning. Of particular interest are the control students' reactions to the two situations of the rowboat and the car. A majority of the students found the rowboat example understandable because they saw in the motion of the water a source or agency for force. However, they saw in the ground no such agency and thus rated the idea of the ground pushing on the tires of the car as less understandable.

These students apparently did not treat the situations simply as collections of features and try to induce an abstract schema for force. Rather, they seemed to reason causally about the situations using their existing models for force. The experimental explanation was perhaps more effective since it engaged the students' models for force and showed how certain of these models could be applicable to the table

situation (a table with the agency of springiness enabling it to exert a force). These ideas are discussed further in the following section.

General Hypotheses Inspired by the Data

Causal Reasoning

Explanatory Canons

At different times in history (and for different people at the same time in history) the kind of description of physical events considered explanatory has varied widely. Kuhn (1977b) calls the different kinds of descriptions "explanatory canons." An explanatory canon encompasses a "paradigm" (Kuhn 1970), the set of explicit and implicit shared assumptions and operating principles of scientists in a particular field of study. For example, scientists functioning in entirely different fields (and thus under different paradigms) can all share the same explanatory canon (e.g. that a system is explained if one can give a formal mathematical description).

Undoubtedly the most famous (and the most ancient) taxonomy of types of explanations is Aristotle's description of the four causes (i.e. types of explanations of phenomena).

> Let us now examine what and how many sorts of explanatory factors there are. All inquiry aims at knowledge; but we cannot claim to know a subject matter until we have grasped the "why" of it, that is, its fundamental explanation. It must clearly, therefore, be our aim in the present inquiry to get knowledge of

> the first principles to which we may refer any problem in our exploration of generation and destruction and of any natural transformation.
>
> "An explanatory factor," then, means (1) from one point of view, the material constituent from which a thing comes; for example, the bronze of a statue, the silver of a cup, and their kinds. From another point of view, (2) the form or pattern of a thing, that is, the reason (and the kind of reason) which explains what it was to be that thing; for example, the factors in an octave are based on the ratio of two to one and, in general, on number. This kind of factor is found in the parts of a definition. Again, (3) the agent whereby a change or state of rest is first produced; for example, an adviser is "responsible" for a plan, a father "causes" his child, and, in general, any maker "causes" what he makes, and any agent causes what it changes. Again, (4) the end or the where-for; so, when we take a walk for the sake of our health, and someone asks us why we are walking, we answer, "in order to be healthy," and thus we think we have explained our action. (Quoted in Averill, 1976, p. 136)

Aristotle's first type of explanation, the "material cause," has been largely abandoned as constituting a kind of explanation, but the other three types of explanation are still used. To the questions, "why is that ball accelerating down the hill?" or "why did John hit Jim?" formal explanations might be that the ball is following a particular equation of motion and that John is a mean person. The "efficient causal" explanations might be that the ball is accelerating down the hill because gravity is exerting a downward force on the ball which is partially countered by the normal force from the hill, and John hit Jim because Jim insulted him causing an aggressive reaction. Teleological explanations from "final causes" might be that the ball is seeking a lower energy state, and John wanted to knock out Jim so he could steal his wallet.

<u>Students Need to Reason Causally</u>

An educational issue which arises from the preceding discussion is that of the explanatory canons of students. As it is most frequently taught, physics uses a predominantly formal explanatory canon, that is, the material is considered explained if careful arguments are presented showing the development of concepts from previous formalisms. Thus, velocity is presented as the quotient of distance and time, force as the product of mass and acceleration, resistance as the quotient of voltage and current, etc. Further relationships are developed and considered explained when the formal interrelationships are articulated. This state of affairs may be less than optimal if the student's explanatory canon, which governs what type of explanation he or she will consider explanatory, is not predominantly formal.

One question of current interest in physics education is whether time should be devoted to the development of qualitative causal models for physical phenomena or whether this constitutes an unnecessary sidetrack from the main business of presenting a formal structure which has enormous power in terms of making precise predictions about the outcomes of experiments in physics. The preferred style of explanation in physics has moved from the teleological explanations of the ancients (e.g. Aristotle's celestial kinematics) to the mechanical causal explanations preceding and following Newton, to the present preference for formal mathematical thought (cf. Kuhn 1977b). Largely because of the bent toward formal explanation in modern physics, causal explanations are viewed with suspicion. Even accepting that the goal of physics

education is to bring students to facility with formal mathematical reasoning about physical situations, there is a question as to whether it is pedagogically advisable to move quickly over causal explanations and on to more elegant formalisms.

Helping students reason formally about physical situations is certainly one of the goals of modern physics education. However, in the case of misconceptions about force, naive causal reasoning militates against effective formal reasoning about the situation. For example, the student may have trouble admitting that the book on the table situation is an example of Newton's third law because for an object to exert force it must have a type of causal agency which allows it to exert a force, and to the student the table is just an inanimate, stationary, rigid object. In many cases it seems that students need to decide on the "causal reasonableness" of a principle or concept before being able to reason effectively using that principle or concept in a formal way.

Newton, who himself struggled with notions of force as a property of objects, apparently found the consideration of the compressibility or springiness of all matter important in his initial thinking about force, as his first definition of force was "the pressure or crowding of one body on another" (Herivel 1965 p. 5). Springiness appears to be a prototypical example of a model which can channel students' causal reasoning away from naive causal reasoning and toward mechanical causality in that it enables the attribution of "person-like" qualities to objects <u>interacting</u> rather than to <u>single</u> objects (as a result of interaction with other objects, springy objects <u>have</u> force or energy

only when compressed or expanded, when they <u>want</u> to get back to their original shapes). In this way viewing matter as springy can serve to help the student progress from a view of force as a property of objects due to characteristics of single objects (e.g. strength, speed, weight) to viewing force as involving an interaction between objects.

I suspect understanding a mechanical system requires the presence of and satisfaction with a causal model of the system. As such, it involves causal reasoning. The position that the growth of abstract logical thought alone underlies conceptual change in science I believe to be misleading. Although advancement to formal operational levels of reasoning is necessary to the understanding of many concepts in physics, it is not sufficient. Advancement in causal reasoning, which involves the attribution of actions to objects and is thus essential in reasoning about mechanical systems, is also necessary to success in physics. I suspect that increased attention to exploring both students' causal reasoning and ways of improving their causal reasoning is likely to have significant educational benefits.

The current studies indicate that instruction can be effective which attempts to help students replace their naive causal models with more adequate models. These studies also indicate that an instructional strategy which is aimed at replacing inadequate models with more adequate models is more effective than a strategy which simply illustrates an abstract principle with examples of situations to which the principle applies. The students seemed to treat these examples not as neutral representations from which they could abstract common features, but rather they treated them as situations about which

they reasoned causally using whatever models were available to them. Thus, with both explanations the students reasoned causally about the thought situations, but the experimental explanation was designed to engage this causal reasoning and use it to advantage, whereas the control explanation did not attempt to channel the students' causal reasoning but rather seemed to simply ignore it.

Analogical Reasoning

Two Types of Analogy Relation

When I began work on these studies, I recognized that both analogical reasoning and the establishment of a causal model were involved in the experimental explanation (by a model I mean both the general model of the table as springy as well as the deeper model of the table as composed of molecules connected by springy bonds). I have since come to a deeper appreciation of the relationship between these two components of the strategy. In what follows I will first discuss two types of analogy relation and then discuss my current belief that the bridging strategy and causal reasoning are interwoven (at least for this domain).

Black (1962a) and Schon (1963) both discuss the comparison view of analogy relations. This view is articulately presented in its most complete form in Gentner's (1980) structure mapping theory in which an analogy relation is seen as the comparison of two systems. As a result of this comparison or mapping, relationships in the base are

transferred to the target. The target is viewed as if it were the base. Thus, for example, electromagnetic waves are viewed as if they were water waves and an electric circuit is viewed as if it were a system of water pipes.

Black (1962a, 1962b) discusses another perspective on analogy relations, that of the base viewed as being the target. For example, in the statement "the table is a spring," the table can be viewed not as though it were like a spring, but it can be viewed as being a spring and thus having the property of springiness. When one thinks analogically in this way, one can be said to have been "captured" by the analogy or model. Either one cannot or one does not wish to view the target in any terms other than those supplied by the base (Black 1962a). One does not stand back as an objective observer and compare two systems "out there," rather the base serves as the spectacles through which one views the target and by which particular aspects of the target are viewed as important and others are ignored.

In science, both ways of thinking analogically play a part. Comparisons have frequently been made between different concepts in science largely for purposes of heuristic value. In discussing Maxwell's early conception of the luminiferous ether Black states that "...the fluid seems at first to play the part merely of a mnemonic device for grasping mathematical relations more precisely expressed by algebraic equations held in reserve. The 'exact mental image' he professes to be seeking seems little more than a surrogate for facility with algebraic symbols" (1962b p. 227).

At this point Maxwell apparently saw simply a comparative analogy between the behavior of electromagnetic phenomena and the behavior of fluids. However, at some point Maxwell was "captured" by the analogy. "Before long, however, Maxwell advances much farther toward ontological commitment. In his paper on action at a distance, he speaks of the 'wonderful medium' filling all space and no longer regards Faraday's lines of force as 'purely geometric conceptions.' Now he says forthrightly that they 'must not be regarded as mere mathematical abstractions. They are the directions in which the medium is exerting a tension like that of a rope, or rather, like that of our own muscles.' Certainly this is no way to talk about a collocation of imaginary properties. The purely geometrical medium has become very substantial" (Black 1962b p. 227). Thus, to Maxwell, the ether became more than simply a comparative analogy (in which the ether was viewed as <u>like</u> a fluid in that certain structural and functional relationships were similar) when he began to view it <u>as being</u> a fluid.

Returning to the present studies, after the third paragraph in the experimental explanation in the written instrument study there is evidence that only one student saw the table at this point <u>as being</u> a spring. In their explanations about why they thought the book on the spring and the hand on the spring were or were not different, only one mentioned anything about the table being springy or flexible, although 11 students saw the situations as analogous. It would seem that for the other 10 students the analogy was simply a comparison, the table

being <u>like</u> a spring in that it too must exert force to hold the book in place.

However, by the end of the explanation, only two students clearly indicated that they believed the table was not springy, while 34 of the 40 experimental students clearly indicated that they now thought the table was springy to some extent. Apparently the explanation was successful for the majority of the students in helping them see the table <u>as being</u> a spring, thus changing their model of the table (at least temporarily) from that of a rigid object without the agency necessary to be able to exert force to that of an object with the agency of springiness enabling it to exert force.

Bridging and Models

With the terminology developed above, it is now possible to hypothesize that the the experimental teaching strategy was effective because it helped the student to construct a new causal model of the table by helping him or her to establish an <u>as being</u> relationship between a table and a spring. Although some students seemed to find an <u>as if</u> relationship sufficient by relating the book on the table to the book on the hand or the book on the spring without seeing the table as being muscular or springy (using the indirect causal argument that the table must exert a force as in these other situations so the book would not fall), many students apparently required this deeper ontological commitment to the relationship between these situations and

the book on the table before they would admit that the situations were analogous.

It appears from the above discussion that many students may need to be able to reason causally in a similar way about two situations before they are willing to accept an analogical relationship between the two situations. For many students, it may not be enough to simply argue that two situations must be analogous since similar effects are observed in each (although such indirect causal reasoning may be important to the overall establishment of an analogical connection). From this I suspect that issues of analogical reasoning and causal reasoning are interwoven, and efforts to understand one can be greatly aided by and can greatly aid efforts to understand the other.

Implications for Teaching

To return to an epistemological point, learning can be viewed as the interaction between sensory experiences and previously existing conceptions. The results of these studies indicate that a serious effort to take existing student conceptions into account, both positive anchors and negative misconceptions, may reap significant educational benefits. The results show that it is possible in some cases to alter student beliefs with carefully chosen thought situations, without the benefit of additional empirical experience, when students' positive anchoring intuitions are extended to target problems involving misconceptions. In saying this, I do not mean to downplay the importance of empirical evidence and concrete experiences in learning

science, but I do wish to highlight the important role that can be played by thought situations as well.

However, the results also indicate that some methods of using thought situations may be less effective than others. For the book on the table (target) post question, all seven students in the interviewing study who received the experimental explanation expressed a confident belief in an upward force from the table, whereas of the seven receiving the control explanation, five refused to accept the conclusion of an upward force, even though the latter explanation had given the correct answer to this problem explicitly. There were also significant differences in performance on the other (transfer) post questions in the interviewing study in favor of the experimental explanation, and there were some important differences in performance and confidence and sense ratings in the written instrument study. These data provide further evidence that the experimental subjects' understanding of the concept was superior.

The traditional use of thought situations, exemplified by the control explanation, is to treat them as examples of an abstract principle demonstrating the types of situations to which that principle applies. However, these studies indicate that this approach may be ineffective when the student holds a misconception. There are indications that there was not a successful process of induction for generating or confirming an abstract schema in a form that could be applied to the post problems. Evidence from the current studies indicate three possible reasons for the observed differences in student response to the two explanations.

1) Some of the individual examples in the control explanation were counter-intuitive to many students (e.g. the runner and the stone). However, most examples in the experimental explanation tended to make sense to the students. In particular, all students said that the anchoring example of the hand pushing on the spring made sense to them intuitively.

2) In some cases examples in the control explanation made sense to the students by tapping their intuition (e.g. the rifle kick), but students could not see an analogical connection to the book on the table situation. However, the experimental explanation put an emphasis on developing such connections by presenting the analogous cases as an ordered chain of connected examples.

3) In the control explanation, students were left wondering about how the table could possibly exert a force. Helping the student construct a mechanistic (i.e. mechanically causal) model of a situation evoking a misconception can be an important step in helping a student change his or her conception of the situation. Some students may even require a mechanistic model which makes sense to them before they will change their conception of a situation.

The present studies indicate that the use of thought situations can be an effective means for bringing about conceptual change and growth in students. Further, if the conclusions of these studies are confirmed in

other domains, this means that the particular method one uses in example-based teaching can be crucial to learning outcomes. Teachers need to be aware that certain examples they themselves find compelling may not be at all illuminating for the student. Even when the example is compelling to the student, it may not be seen as analogous to the target problem in the lesson. Such analogical connections of qualitative similarity are not always obvious, and may require attention in instruction through techniques such as bridging.

Finally, teachers need to keep in mind the goal of helping students develop visualizable, qualitative, causal models of physical phenomena. I doubt that the cure for misconceptions lies in resorting to purely formal approaches in hopes of bypassing causal reasoning, as causal reasoning appears to be an important component of students' thinking about mechanical systems. Rather, approaches should be developed which use the students' ability to reason causally and which channel their causal reasoning away from naive causal reasoning and toward mechanical causality.

Implications for Future Research

Need to Pursue a Coherent Theory of Instruction

I have argued previously that a coherent theory of instruction is necessary in order to raise curriculum design efforts from the level of the trial and error application of general constructivist strategies (e.g. actively involving the student) to the consistent application of a

sound instructional theory. Resnick (1983) identifies three components of a theory of instruction: 1) a specification of the capabilities the student already has and those to be acquired; 2) a description of how those capabilities are acquired; and 3) a specification of how to intervene to encourage the acquisition of the capabilities.

She identifies two levels at which such a theory could be specified, the behavioral level and the cognitive level. In the exploration of students' concepts about science, a great deal of effort has been invested in exploring the first component of a theory of instruction at the behavioral level by cataloguing the types of questions with which students have difficulties. These studies have led to attempts to specify alternative frameworks at the cognitive level, which are usually stated in terms of rules. Some examples of such rules are: "if an object is moving then there is a force causing the motion," "if an object is moving in a direction then there is a force on that object in that direction," "if two objects interact, then the object with the greater mass exerts the greater force." (See Aguirre and Erickson, 1984, and Maloney, 1984, for examples of the specification of students' rules.)

Although such studies are of fundamental importance (both studies cataloguing students' behavioral errors and studies attempting to specify cognitive rules underlying and governing the observable behaviors), the rules themselves may rest on an underlying substrate of mental models - cognitive representations which are much richer than specific rules they generate. These models may frequently involve

static or dynamic mental imagery - visual, kinesthetic, and/or auditory.

Models

Students' Mental Models

Clement (1982a), in investigating the problem solving behavior of expert problem solvers on a conceptually difficult problem, observed the generation of a number of mental models which were frequently progressively refined until the subject placed a high degree of confidence in them. Larkin (1983) considers the construction of a mental model or physical representation an essential part of the solution process for physics problems. These studies indicate that mental models may be important to the conceptual understanding necessary for effective problem solving.

Driver (1984) questions the sole use of conflict in effecting conceptual change, arguing that the use of metaphor is important in allowing students to make connections between their existing knowledge and a new theory or construction. Osborne and Wittrock (1983) discuss the central place of models in children's thinking. Clement (1983b) suggests that conceptual models or metaphors may underlie common misconceptions, for example the "impetus force dying away" model. Learning would then occur when the old model is replaced with a new one, for example the "frictional force whittling away at velocity" model. It may be argued here that students do not refer to a conscious model such

as those described by Clement. However, although students may not be able to consciously articulate the model which underlies their reasoning, they may be driven by what some have called "underground" or "implicit" models.

Underground or Implicit Models

Black (1962b) describes a type of model which he calls "an implicit or submerged model." This is a model which structures a person's thinking without that person making conscious reference to the model. In a similar vein, Kaput (1979), in discussing student understanding of calculus concepts, describes what he calls silent or secret metaphors. He considers the example of the concept of limit and suggests that typically undergraduates encountering this concept base their understanding of it on a motion metaphor. This metaphor is certainly reinforced by language (indicating the roots of the concept) such as "the limit of f(x) as x approaches zero."

It was a great struggle for mathematicians trying to clarify the concept of limit to purge their thinking of this metaphor and invent the motionless epsilon-delta definition of limit. According to Kaput, students of today encounter a similar struggle. "When we try to squeeze the motion metaphor from an undergraduate's understanding of limit and replace it with epsilons and deltas, then, of course, the epsilons start moving (toward zero, naturally). If we can stop the epsilons, then the deltas start moving. If finally, through coercion and threats, we are

able to stop the epsilons and deltas, everything stops, especially thinking." (Kaput 1979, p. 295)

Schon (1979) offers another example of implicit metaphors in the domain of social policy. He argues that inquiry into social policy is seen as a kind of problem solving. The problems are already assumed to be known, the policymaker's task is to pursue paths which will solve these problems. However, what is not recognized here is the extent to which problem setting influences attempts at solutions. If slum areas are viewed as "urban blight," the problem becomes one of excising the disease from the community. However, if slum areas are viewed as natural communities of low income people similar to communities in many poorer nations, the problem is seen in an entirely different light.

Lakoff & Johnson (1980) discuss a wide variety of implicit metaphors, or "metaphors we live by." These include "argument is war" (warriors are seen to be defending claims, shooting down arguments, using strategies, and winning); "time is money" (time is invested, saved, wasted, budgeted, etc.); and orientational metaphors such as "good is up, bad is down" (e.g. things being at an all-time high or low). Their claim is that metaphor is pervasive in language (even in language believed to be "literal") and equally pervasive in thought.

Students Need to Replace or Modify Models

The above authors present a compelling case that thinking may be largely mediated by implicit as well as explicit models or metaphors. If such is the case, then students' models might give rise to

misconceptions and may need to be modified or replaced by more appropriate models. The bridging analogies approach explored in the current studies drew a great deal of its initial impetus from studies of experts' use of models in problem solving situations (Clement 1982a, 1985a, 1985b, 1986a). Some of the strategies experts used in attempting to construct new conceptual models, such as the generation of intermediate models, were modified and used with students in the analogical teaching technique described above.

This technique is an example of a strategy designed to help the student replace or modify an inappropriate model (e.g. rigid objects unable to exert forces) with a more appropriate model (all objects are springy to some extent, or, at a deeper level, all objects are composed of molecules connected by springy bonds, and thus are able to compress and exert force). By consideration of a connected sequence of thought situations beginning with a situation which invokes the appropriate model (e.g. a hand pressing on a spring), the student may then be able to replace the naive model with the more adequate model, giving rise to more nearly correct responses to problem situations which would previously have invoked the naive model of rigid objects.

Future Directions

A number of studies, including the current studies, report significant gains in students' conceptual understanding with the use of innovative teaching strategies. These strategies were based on a constructivist perspective in which the teacher is viewed as the

facilitator helping the student to actively grapple with the concepts. However, although some success has been achieved in recent explorations, the success has been sporadic and unpredictable. What is needed is a well developed theory of instruction.

In order to generate such a theory, efforts need to continue at three levels - the behavioral level of cataloguing student errors, the underlying cognitive level of specifying rules, and the deeper cognitive level of analysing students' models which underlie the rules. Although a great deal of effort has been devoted to research at the level of cataloguing student errors and a smaller amount of effort to specifying students' cognitive rules, very little effort has been devoted to analysing students' models. All of these levels could be explored in separate studies or in conjunction with teaching experiments designed to test various methods of remediating alternative student conceptions. With the latter, not only could students' models be examined, but the effects of various teaching strategies on these models could be explored.

In a sense the current situation in the study of misconceptions is reminiscent of the state of classical mechanics prior to Newton. Kinematics, the careful description and analysis of observed motions, had been advanced by Galileo. But the causes underlying the observed motions had not yet been explicated. In the study of students' alternative conceptions, it may be necessary to go beyond the behavioral and cognitive "kinematics" stages of cataloguing student errors and specifying cognitive rules in order for a carefully articulated theory of instruction to be forthcoming. What may be

required is a careful analysis of the explicit and implicit models by which students' thinking is governed and an analysis of the interaction of different types of instruction with these models.

NOTES

1) In the literature there is no agreed upon standard vocabulary for discussing alternative student beliefs. Misconceptions, alternative frameworks, alternative conceptions, and children's science are several of the terms used to describe ideas students bring to class with them which are in conflict with the material being taught. Throughout this review, these terms will be used interchangeably.

2) In this review I will not use the term "misconception" to refer to the misconstrual of formal instruction, although this is a common usage of the term. Rather, it will refer to preconceptions or beliefs the student holds which are in opposition to accepted scientific theory and which the student forms outside of the classroom.

3) Rutherford, F. J., Holton, G., & Watson, F. G. (Eds.) (1981). Project Physics Text. United States of America: Project Physics.

APPENDIX A

INTERVIEWING INSTRUMENT

This appendix contains the instrument I used during the interviews. Contained in this appendix are the following:

1) A definition of force.
2) Pre and post-questions: Table, Goat, and Mosquito problems (asked both before and after the explanation) and the Two Boxes and Steel Blocks problems asked only after the explanation.
3) A page explaining the makes sense scale and distinguishing sense from confidence.
4) The explanations.
5) The probes used during the explanations.
6) Post-explanation ratings - how understandable and believable the explanation was and how much the explanation helped the idea of an upward force from the table make sense.

Definition of Force

Following is the definition of force which the students read at the beginning of the interview.

Since the rest of this exercise will deal with the idea of force, force is defined below:

A force is a push or a pull of one object on another object.

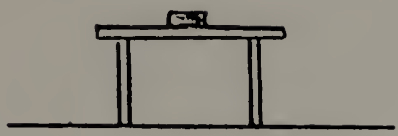
Pre and Post-Questions

Following are the questions which were asked before and after the student interacted with the explanation. Three of these questions (the Table Problem, the Goat Problem, and the Mosquito Problem) were asked both before and after the explanation, and two (the Two Boxes Problem and the Steel Blocks Problem) were asked only after the explanation. After each question (and after each part of the two part questions) students were asked to indicate how confident they were in their answer using the scale below. They could mark their confidence anywhere along this scale.

0	1	2	3
Just a blind guess	Not very confident	Fairly confident	I'm sure I'm right

TABLE PROBLEM

A book is at rest on a table.



Which of the following do you think is true?

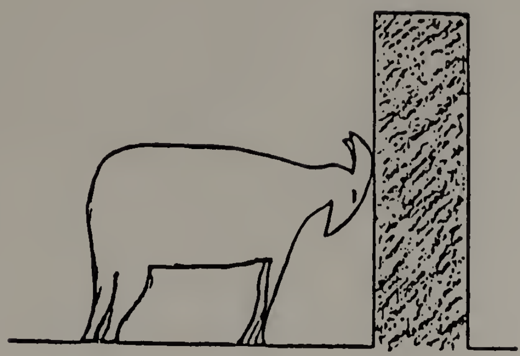
___The table exerts a force upward on the book.

___The table does not exert an upward force on the book.

Please explain why you think the table exerts or does not exert a force up on the book.

GOAT PROBLEM

A stubborn goat is pushing against a wall.



While the goat is pushing, does the wall exert a force back on the goat?

___1) Yes

___2) No

If you said <u>yes</u>:

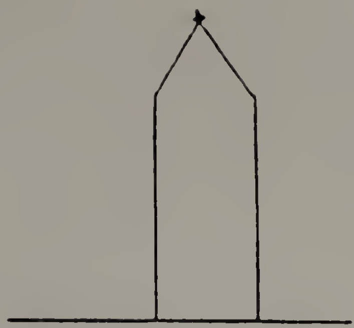
___A) The wall exerts a force back on the goat which is larger than the goat's force on the wall.

___B) The wall exerts a force back on the goat which is smaller than the goat's force on the wall.

___C) The wall exerts a force back on the goat which is the same size as the goat's force on the wall.

MOSQUITO PROBLEM

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.

While the mosquito is resting there, does the monument exert an upward force on the mosquito?

___1) Yes

___2) No

If you said yes:

___A) The monument and the mosquito each exert a force on the other, but the mosquito exerts a larger force.

___B) Each exerts a force, but the monument exerts a larger force.

___C) Each exerts a force, and the forces are the same size.

___D) Only the monument is exerting a force.

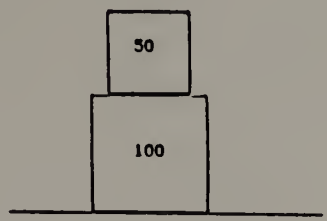
If you said no:

___E) The mosquito exerts a force on the monument.

___F) The mosquito does not exert a force on the monument.

TWO BOXES PROBLEM

A box weighing 50 pounds rests on top of another box weighing 100 pounds. Think about whether the upper box exerts a force on the lower box and whether the ground exerts a force on the lower box.



Does the ground exert an upward force on the lower box?

____1) Yes

____2) No

If you said yes:

____A) Both the ground and the upper box exert forces on the lower box, but the upper box exerts the larger force.

____B) Both the ground and the upper box exert forces on the lower box, but the ground exerts the larger force.

____C) Both the ground and the upper box exert forces on the lower box, and these forces are the same size.

____D) Only the ground exerts a force on the lower box.

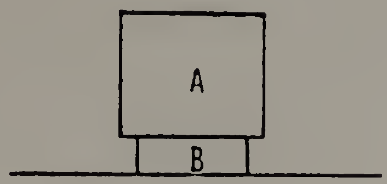
If you said no:

____E) The upper box exerts a force on the lower box.

____F) The upper box does not exert a force on the lower box

STEEL BLOCKS PROBLEM

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.



Does B exert an upward force on A?

___1) Yes

___2) No

If you said yes:

___A) A and B each exert a force on the other, but A exerts a larger force.

___B) Each exerts a force, but B exerts a larger force.

___C) Each exerts a force, and these forces are the same size.

___D) Only block B exerts a force.

If you said no:

___E) Block A exerts a force on block B.

___F) Block A does not exert a force on block B.

Makes Sense Scale

Throughout our lives, we have had a wealth of experience with the physical world which leads us to feel that some things make sense and other things don't. A statement makes sense when we understand it at an intuitive or "gut" level.

There are times when we know an answer is correct, (that is we are very confident in our answer) but it doesn't really make sense. For example, many people are confident that if a person throws a boomerang, it will circle around and come back. But it doesn't make sense to them that it should come back. What makes sense to them is that the boomerang should just go in a straight line.

At other times, we are confident about an answer, and it makes perfect sense. For example, if a large truck runs into a small car, most people are confident that the car will get damaged. It also makes sense to them that the car would be damaged.

For the question the interviewer shows you, please rate how much sense each answer makes using the scale below. (Note: When you give your ratings, please rate how much sense each answer makes, not how confident you are that the answer is correct.)

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

The Explanations

Following are the explanations with which the students interacted in the interviews. Both the control and experimental explanations which the students saw occupied only a single page, but because of the margin requirements of the dissertation, neither explanation can fit onto one page.

The Control Explanation

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Newton's third law says that the table does exert a force on the book. Newton's third law states: To every action there is always opposed an equal reaction: or, mutual actions of two bodies upon each other are always equal and directed to contrary parts. This is a word-for-word translation from the Principia. In modern usage, however, we would use force where Newton used the Latin word for action. So we could rewrite this passage as follows: If one object exerts a force on another, then the second also exerts a force on the first; these forces are equal in magnitude and opposite in direction.

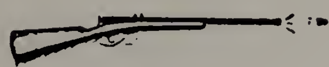
Apply this idea to an athlete running. You now see that her act of pushing with her feet back against the ground (call it the action) also involves a push of the ground forward on her (call it the reaction). It is this reaction that propels her forward.

In this and all other cases, it really makes no difference which force you call the action and which the reaction, because they occur at exactly the same time. The action does not "cause" the reaction. If the earth could not "push back" on her feet, the athlete could not push on the earth in the first place. Instead, she would slide around as on slippery ice. Action and reaction coexist. You cannot have one without the other. Most important, the two forces are not acting on the same body. In a way, they are like debt and credit. One is impossible without the other; they are equally large but of opposite sign, and they happen to two different objects.

Newton wrote: "Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone." This statement suggests that forces always arise as a result of mutual actions ("interactions") between objects. If object A pushes or pulls on B, then at the same time object B pushes or pulls with precisely equal force on A. These paired pulls and pushes are always equal in magnitude, opposite in direction, and on two different objects.

Every day you see hundreds of examples of this law at work. A boat is propelled by the water that pushes forward on the oar while the oar pushes back on the water. A car is set in motion by the push of the ground on the tires as they push back on the ground; when friction is not sufficient, the push on the tires cannot start the car forward.

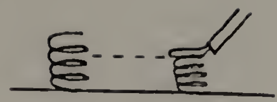
While accelerating a bullet forward, a rifle experiences recoil, or "kick." A balloon shoots forward while the air spurts out from it in the opposite direction. Many such effects are not easily observed. For example, when an apple falls, pulled down by its attraction to the earth, i.e., by its weight, the earth, in turn, accelerates upward slightly, pulled up by the attraction of the earth to the apple.



To summarize, many people say the table is not exerting a force upward on the book. However, the book is exerting a force downward on the table because of its weight. Therefore, because of Newton's third law, the table is exerting an equal force upward on the book.

The Experimental Explanation

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Consider pushing down on a spring with your hand.

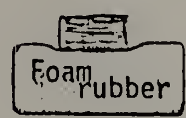


Now consider the case of a heavy dictionary being placed on a bedspring so the spring compresses some.

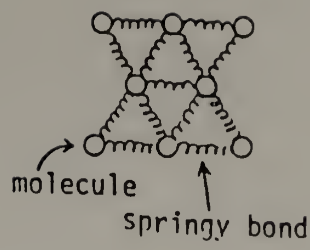
When the book is placed on the spring, the spring compresses. The further down the spring is pushed, the more it pushes back. The spring is compressed by the book to the point where it pushes back with a force equal to the book's weight. For example, if the book weighs 10 pounds, the spring compresses until it exerts an equal upward force of 10 pounds. In a similar way, if you hold a 30 pound dictionary in your outstretched hand, you have to exert an upward force of 30 pounds to hold it there.

Many people say the book on the spring is different than the book on the table. They say that although neither is alive, the spring compresses but the table is rigid. But is the table rigid? Imagine a flexible board between two sawhorses. If you were to push down on this board it would bend and push back, just like pushing down on the spring. The board would also push back on a book, just like the spring. Now imagine thicker and thicker boards.

If you had a thick enough board, it would be just like a table. Both the board and the table would bend a tiny, tiny bit under the weight of a book. Another way to think of the table is like very stiff foam rubber. Even though the stiff foam rubber would not compress much under the weight of a book, it would compress some.



The table is composed of molecules which are connected to other molecules by bonds which are "springy." Thus the table has some amount of give or "bendiness" or "squishiness" to it. If you were to look closely with a microscope you would see that the book causes a slight depression in the table. The table, just like the spring, the flexible board, or foam rubber, is bent or compressed some and thus pushes back. Like the spring holding the dictionary, the table bends or compresses just enough to provide an upward force equal to the book's weight.



To summarize, many people do not think the table can exert a force since it is rigid and lifeless. However they feel a spring can exert a force if a force is exerted on it because it "wants to get back to its original shape." Thus there seems to be a distinction between rigid objects and springy objects. However, if you look closely enough at a table it <u>is</u> springy because of its molecular makeup. Because of this springy nature of <u>all</u> matter, the table can and does exert a force upward on the book. Just like a spring, the table compresses (on a microscopic scale) until it is compressed enough to provide an upward force equal to the book's weight.

Probes Used During the Control Explanation

Following are the introduction I gave to the student about the control explanation and the planned probes after each paragraph. The student did not see these probes in a written form, but rather I asked them orally. (Note: If the student did not volunteer his or her reactions after reading each paragraph, I began with the general probe "What are you thinking?" after each paragraph.)

What I'm going to do now is give you an explanation about the book on the table situation, and I'm going to ask you along the way about how understandable it is. At the end I'm going to ask you how understandable the explanation is as a whole.

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Newton's third law says that the table does exert a force on the book. Newton's third law states: To every action there is always opposed an equal reaction: or, mutual actions of two bodies upon each other are always equal and directed to contrary parts. This is a word-for-word translation from <u>the Principia</u>. In modern usage, however, we would use <u>force</u> where Newton used the Latin word for action. So we could rewrite this passage as follows: If one object exerts a force on another, then the second also exerts a force on the first; these forces are equal in magnitude and opposite in direction.

Can you state Newton's third law in your own words?

Is the statement "for every force there is an equal and opposite force" understandable and believable to you?

Rating:______

Apply this idea to an athlete running. You now see that her act of pushing with her feet back against the ground (call it the <u>action</u>) also involves a push of the ground forward on her (call it the <u>reaction</u>). It is this reaction that propels her forward.

Does it make sense to you that the ground pushes forward on the athlete?

Sense rating:______

In this and all other cases, it really makes no difference which force you call the action and which the reaction, because they occur at exactly the same time. The action does not "cause" the reaction. If the earth could not "push back" on her feet, the athlete could not push on the earth in the first place. Instead, she would slide around as on slippery ice. Action and reaction coexist. You cannot have one without the other. Most important, the two forces are not acting on the same body. In a way, they are like debt and credit. One is impossible without the other; they are equally large but of opposite sign, and they happen to two different objects.

Can you say in your own words what this paragraph is trying to argue?

Newton wrote: "Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone." This statement suggests that forces always arise as a result of mutual actions ("interactions") between objects. If object A pushes or pulls on B, then at the same time object B pushes or pulls with precisely equal force on A. These paired pulls and pushes are always equal in magnitude, opposite in direction, <u>and on two different objects</u>.

Can you say in your own words what this paragraph is trying to argue?

Does it make sense to you that the stone would push back on the finger?

Sense rating:______

Every day you see hundreds of examples of this law at work. A boat is propelled by the water that pushes forward on the oar while the oar pushes back on the water. A car is set in motion by the push of the ground on the tires as they push back on the ground; when friction is not sufficient, the push on the tires cannot start the car forward.

Can you say in your own words what this paragraph is trying to argue?

For each of these examples of the third law, could you say if it makes sense to you?

Rowboat______

Car______

While accelerating a bullet forward, a rifle experiences recoil, or "kick." A balloon shoots forward while the air spurts out from it in the opposite direction. Many such effects are not easily observed. For example, when an apple falls, pulled down by its attraction to the earth, i.e., by its weight, the earth, in turn, accelerates upward slightly, pulled up by the attraction of the earth to the apple.

Can you say in your own words what this paragraph is trying to argue?

For each of these examples of the third law, could you say if it makes sense to you?

Rifle______

Balloon______

Apple______

Do the examples in the last two paragraphs make the statement "For every force there is an equal and opposite force" understandable and believable?

Rating:______

To summarize, many people say the table is not exerting a force upward on the book. However, the book is exerting a force downward on the table because of its weight. Therefore, because of Newton's third law, the table is exerting an equal force upward on the book.

Is the explanation on this page understandable and believable to you?

Does the explanation on this page help the idea of an upward force from the table make sense?

Rating:______

Which examples on this page helped the idea of an upward force from the table make sense and which did not help?

Probes Used During the Experimental Explanation

Following are the introduction I gave to the student about the experimental explanation and the planned probes after each paragraph. The student did not see these probes in a written form, but rather I asked them orally. (Note: If the student did not volunteer his or her reactions after reading each paragraph, I began with the general probe "What are you thinking?" after each paragraph.)

What I'm going to do now is give you an explanation about the book on the table situation, and I'm going to ask you along the way about how understandable it is. At the end I'm going to ask you how understandable the explanation is as a whole.

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Consider pushing down on a spring with your hand.

Does it make sense to you that the spring would push up on your hand?

Sense rating:______

Is this different from the book on the table?

Now consider the case of a heavy dictionary being placed on a bedspring so the spring compresses some.

Does it make sense to you that the bedspring pushes up on the book?

Sense rating:______

When the book is placed on the spring, the spring compresses. The further down the spring is pushed, the more it pushes back. The spring is compressed by the book to the point where it pushes back with a force equal to the book's weight. For example, if the book weighs 10 pounds, the spring compresses until it exerts an equal upward force of 10 pounds. In a similar way, if you hold a 30 pound dictionary in your outstretched hand, you have to exert an upward force of 30 pounds to hold it there.

Does it make sense to you that the spring would exert a force of 10 pounds up on a book weighing 10 pounds?

Sense rating:______

Is this different from the book on the table?

Many people say the book on the spring is different than the book on the table. They say that although neither is alive, the spring compresses, but the table is rigid. But is the table rigid? Imagine a flexible board between two sawhorses. If you were to push down on this board it would bend and push back, just like pushing down on the spring. The board would also push back on a book, just like the spring. Now imagine thicker and thicker boards.

Does it make sense to you that the flexible board pushes up on the book?

Sense rating:______

What would happen if the board got thicker and thicker?

Is the book on the board situation different from the book on the table?

If you had a thick enough board, it would be just like a table. Both the board and the table would bend a tiny, tiny bit under the weight of a book. Another way to think of the table is like very stiff foam rubber. Even though the stiff foam rubber would not compress much under the weight of a book, it would compress some.

Does it make sense to you that the foam rubber pushes up on the book?

Sense rating:______

Is the book on the stiff foam rubber situation different from the book on the table?

The table is composed of molecules which are connected to other molecules by bonds which are "springy." Thus the table has some amount of give or "bendiness" or "squishiness" to it. If you were to look closely with a microscope you would see that the book causes a slight depression in the table. The table, just like the spring, the flexible board, or foam rubber, is bent or compressed some and thus pushes back.

Like the spring holding the dictionary, the table bends or compresses just enough to provide an upward force equal to the book's weight.

Is the table deformable or squishy at all?

To summarize, many people do not think the table can exert a force since it is rigid and lifeless. However they feel a spring can exert a force if a force is exerted on it because it "wants to get back to its original shape." Thus there seems to be a distinction between rigid objects and springy objects. However, if you look closely enough at a table it <u>is</u> springy because of its molecular makeup. Because of this springy nature of <u>all</u> matter, the table can and does exert a force upward on the book. Just like a spring, the table compresses (on a microscopic scale) until it is compressed enough to provide an upward force equal to the book's weight.

Is the explanation on this page understandable and believable to you?

Rating:______

Does the explanation on this page help the idea of an upward force from the table make sense?

Rating:______

Which examples on this page helped the idea of an upward force from the table make sense and which did not help?

Student Ratings of the Explanations

Following are the scales which the students used to answer the two questions:

1) Is the explanation on this page understandable and believable to you?

2) Does the explanation on this page help the idea of an upward force from the table make sense?

UNDERSTANDABLE AND BELIEVABLE?

1	2	3	4	5
Not at all	Slightly	Moderately	Very	Completely

HELPS TO MAKE SENSE?

1	2	3	4	5
Not at all	Slightly	Moderately	A good amount	A great deal

APPENDIX B

CONTROL CASE STUDY TRANSCRIPT

TRANSCRIPT

Cognitive Processes Research Group
University of Massachusetts

Name: Curt (not his real name)
Problem: Control Explanation
Interviewer: D. Brown

001 I: Okay, here's the first thing, it's not really a question, it's the definition of Force. If you could just read that out loud then we can move on.
002 S: Read it out loud. "Since the rest of this exercise will deal with the idea of force, force is defined below: A force is a push or a pull of one object on another object."
003 I: How does that sound?
004 S: It sounds right.
005 I: Okay.
006 S: I mean, you know, it's kind of a basic statement.
007 I: Okay. Okay, great. Let's put this over here. Here's the first question if you could just read that, and respond to it. If you could just read that out loud that really helps.
008 S: "A book is at rest on a table. Which of the following is true: The table exerts a force upward on the book. The table does not exert an upward force on the book." So I'm supposed to say: Just a guess, not very confident, fairly confident, I'm sure I'm right.
009 I: Yeah, that's a confidence scale where you can just say how sure you are of your answer.
010 S: Okay, I'd say that it's not exerting an upward force on the book, because the table isn't pushing upwards towards the ceiling, there's no movement in the table whatsoever. Granted you can have, I mean it still has its separate space, but the book is pushing down the table's not pushing up. If there's no
011 table there, you move the table within 3 feet of the book and put the book on the same level, and hold it, it'll fall down to the ground. The table's just acting as a support, not pushing on the book, not exerting a force upward on the book, as it says.
012 I: Okay. If you could just mark your answer and your confidence.
013 S: Can I put it here?
014 I: Sure.
015 S: Do you want me to circle the confidence?
016 I: You can mark it anywhere along that line. Okay thanks. This is something a little bit different. If you could just read that out loud and then we can move on.
017 S: "Throughout our lives, we have had a wealth of experience with

the physical world which leads us to feel that some things make
sense over other..over things that don't. A statement makes
sense when we understand it, it, intuitive or gut level. There
are times when an answer we know is correct, (that we are very
018 confident of our answer) but it doesn't really make sense. For
example, many people are confident that if a person throws a
boomerang, it will circle around and come back. But it doesn't
make sense to them that it should come back. What makes sense
to them is that the boomerang should go in a straight line. At
019 other times, we are confident about an answer, and it makes
perfect sense. For example, if a large truck runs into a small
car, most people are confident that the car will get damaged.
It also makes sense to them that the car would be dam, ah
that,

020 I: I think the emphasis should be on sense, "It also makes sense to
them."

021 S: Oh, and that would make sense then that the car would be
damaged. For the question the interviewer shows you, please
rate how much sense each answer makes using the scale below.
(Note: When you give your ratings, please rate how much sense
each answer makes, not how confident you are that the answer is
correct.)

022 I: In your own words, could you say what is the difference between
being confident about an answer, and an answer making sense?

023 S: Being confident about an answer is more or less, intellectually
feeling that the answer's right. Whether or not it's right or
wrong is immaterial. If you're confident of the answer, you
think it's right, you're happy with it, you're set on it. And
that, whether it's wrong you'll find out later, but that's what
you're going to go with. It's almost like betting, putting your
money on a specific number, you know. And you said an answer
making sense? Between an answer making sense?

024 I: Yeah, how's that different from an answer making sense?

025 S: Um, an answer making sense is after it's been explained to you,
after you've found out what it really is, and then you go into
the details of it, and then they show you how it works because
of this. I mean your answer that you were confident of could
have been the answer that makes the most sense, but, on the same
026 note, it could not have been. And sense is working it out
logically and showing you how it happens.

027 I: Um, an example, um, maybe I could also stress that it's at an
intuitive, or gut level, you know what this scale is, this
particular scale is trying to get at, you know, what you think
at an intuitive or gut level, like for instance, I don't know
about yourself, but a lot of people when they see somebody throw
028 a boomerang, um, you know, they're confident that it's going to
circle around and come back because they've seen that. But it
doesn't really make sense at an intuitive or gut level. I mean,
when you throw something, it goes straight. Um, I don't know,
for some people that's a helpful example. I don't know if it is
for you.

029 S: Well I was looking at it a totally different way. I wasn't
thinking of it in terms of throwing a boomerang, because I know
the mechanics of how the boomerang comes back, in the curving of
the wood and the different levels of wood and stuff. So that
didn't bother me, I didn't even think about that.

030 I: Yeah, so for you it probably is not a very good example. But I
don't know if you can imagine someone, you know, who doesn't
know that stuff, who saw somebody throw a boomerang.

031 S: Yeah.

032 I: I mean, what's going on. That doesn't make sense. you know,
even though they're confident that, you know, if the guy threw
it again it would do the same thing, 'cause they just saw it.
It really wouldn't make sense to them. That's the kind of thing
that we're trying to get at with this, you know, scale; what
your sort of, intuitive or gut level reactions are to things.

033 S: Well, if that's not right, I wouldn't know what it is, I mean
that's the way I'd go about defining both what makes sense and
what, I mean, what makes is logical thinking, I mean the way
you put things and thought process, has been explained to you.
I mean, once something's explained, it makes sense in your mind
because you understand how it goes, or how it works, or what it
does.

034 I: Mm hmm. I think, Yeah, I think it's roughly the same thing.
I mean, I think maybe the contrast would be, um, you may know an
answer is correct because someone told you, that you respect.
But it doesn't feel right to you at all but, you know, that's
what they said, so I'm confident that that's right. So it's
035 probably roughly the same thing. Okay, um, what I'd like you to
do for this question here, is if for each of these statements,
if you could just say how much sense it makes to you. So how
much sense does it make to you that the table exerts a force
upward on the book? And how much sense does it make that the
table does not exert an upward force on the book?

036 S: Um. The first one makes no sense to me at all because when I
think of a force, I think of gravity as the universal force, I
mean there may other, there, I know of hyper force and other
things but, when I think of force, I think of gravity pulling
down. You know? Things falling down. And a table pushing an
upward force is, it just seems odd to me that a table that's
037 inanimate, stays in one place is, and on legs balancing on the
ground, is actually pushing up on something. Because it's not
getting any higher off the ground. It's not moving upward. And
the book is actually staying stationary, but it would fall down
to the ground had there not be a table. So it wasn't, it's not
038 really, it's not really pushing up on it, the book is more
resting on it. And the bottom one makes more sense for this
same reason.

039 I: Okay. So what ah, on this scale here, from 1 to 5, what rating
would you give each of those statements?

040 S: Ah, 2, I'd give 1 this, I'd give it two, because I'm not
exactly sure that that's right. And number 2 on here, I'd

probably give four.
041 I: Four. Okay. Okay, thanks. Put this over here. Thank-you very much, I really appreciate your saying what you're thinking, it's helpful.
042 I: Okay, here's the second one.
043 S: Want me to read this out loud?
044 I: Sure.
045 S: A stubborn goat is pushing against a wall. While the goat is pushing, does the wall exert a force back on the goat? Yes or No? Just a blind guess. Does it? ---- No. ----- Because I said 'Yes I didn't,' is that a blind guess, fairly confident. Because the wall is not pushing back, the wall is standing
046 still. The goat is doing all the pushing, and except for receiving the push, the wall is doing nothing. I could see if it was started to sway towards the goat, and push the goat backwards also. But, more or less, I'd say that the goat is doing the pushing and the wall is not exerting any force against
047 the goat. You know, other than the logical, brick force, you know, the strength of the bricks.
048 I: Okay.
049 S: I put this for that one.
050 I: Okay, and let me ask um, how much sense your answer makes to you. On that scale.
051 S: Uhh, three.
052 I: Three. Okay. And, could you say a little bit about what's behind your sense rating?
053 S: Um, because that seems like the right thing to me. It seems that that would be, that is the most logical way of thinking about it. I mean, the wall is pushing back, ah, I would understand. But I'm not exactly sure that the wall, um, by just being a resisting thing, um, not letting the goat pass through
054 it, isn't exerting a force. It very well could be and I would never notice that.
055 I: Okay, thanks.
056 I: Okay here's the next one.
057 S: The Mosquito Problem. On a day with no wind, a mosquito lands on top of Mt. Washington, oh, Washington Monument, okay. 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. Does the mosquito resting there, while the mosquito is resting there does the ---(15 secs.)---
058 I: What are you thinking?
059 S: I'm just thinking of my actions. I've been saying no so many times that I feel that I'm, that this is like ah, totally the wrong way. No, I have to keep going with no, because I've been saying no. That's the way I think. Inanimate objects seem to make no sense, that they're exerting a force. Except a counter-
060 force of, of resistance. I don't think that it's putting up its own essential force pushing back against the mosquito saying 'no you can't come down here.' I think it's just by being there, it's in the way. That's, and that's right in

here.
061 I: Okay.
062 S: If ah, if I said no, the mosquito exerts a force, yes. There.
063 I: Okay. And for each of the answers that you gave could you say
how much sense it makes to you?
064 S: I'll leave this sheet right there. Okay. This one I'm a little
more confident about, four, I'd say.
065 I: For which one?
066 S: This one.
067 I: Uh huh. Okay.
068 S: Four. And if I said 'No' the mosquito exerts a force on the
monument, and that makes logical sense to me, I'll say three for
that one.
069 I: Three, okay.
070 S: And how confident am I of that? I'm more towards fairly.
071 I: Okay. Okay, thanks. Okay, what I'm going to do now is give you
an explanation about the book on the table situation. And I'm
going to ask you along the way about how understandable it is.
And then at the end I'm going to ask how understandable the
explanation is as a whole.
072 S: Okay.
073 I: So ah, what I'd like to ask you to do is if you could, um, after
reading each paragraph, if you could just stop, you know, at
each break, and just say what you're thinking. And then I'll
probably have another question or two to ask you, and then you
can move on to the next paragraph.
074 S: Okay, want me to read this out loud or just
075 I: Um, yeah, it's helpful for us if you can read it out loud. Some
people have a little trouble reading out loud and thinking about
it at the same time, so if that's a problem, feel free as slowly
as you want or re-read something, or whatever.
076 S: Okay. "In this exercise we will consider the question of whether
a table pushes up on a book resting on it. Newton's third law
says that the table does exert a force on the book. Newton's
third law states: To every action there is always an opposed
equal reaction: or, mutual actions of two bodies upon each other
077 are always equal and directed to contrary parts. This is a
word-for-word translation from the Principia. In modern usage,
however, we would use force where Newton used the Latin word for
action. So we could rewrite this passage as follows: If one
object exerts a force on another, then the second also exerts a
078 force on the first; these forces are equal in magnitude and
opposite in direction." And, know what I'm thinking?
079 I: What?
080 S: I did the first one wrong. And I guess I hadn't thought, I
hadn't thought of something that stays still, I guess it stays
still, stationary, as exerting a counter-force, other than
resistance. And maybe resistance is a force that I am not,
fully, ah, set in using. I obviously haven't accrued enough
knowledge to ah, answer the first one.
081 I: What, which first one?

082 S: This question relating to the book on the table.
083 I: Uh huh. Um, let me ask can you state Newton's Third Law in
your own words?
084 S: Yeah. For every action there's a counter reaction.
085 I: Okay. Is the statement um, "For every force there is an equal
and opposite force," understandable and believable to you?
086 S: Understandable, yes. Believable, um, I've had trouble
believing it because of the reason I said, I can't see
inanimate, stationary objects exerting a force other than
resistance. It, maybe resistance is a force.
087 I: Okay, and let me ask, here's another scale. If you could just
say how understandable and believable that statement is.
088 S: Okay. Understandable, very.
089 I: Okay.
090 S: That's there.
091 I: Okay.
092 S: Believable, I'd say maybe moderately.
093 I: Okay. Great.
094 S: Okay.
095 I: Go ahead whenever you want.
096 S: "Apply this idea to an athlete running. You now see that her act
of pushing her feet against.. ah feet back against the ground
(call it the action) also involves a push of the ground forward
on her (call it the reaction). It is this reaction that propels
her forward." I never would have thought of that. I mean that
097 was not even close to my mind when I was formulating an answer
for that first question.
098 I: Does it make sense to you that the ground pushes forward on the
athlete?
099 S: Um, give me one second and I'll see if it does. ---(15 secs)---
Honestly? Not a whole lot, of sense, I mean, I get a draft of
what they're saying, but I can't really understand the logic
behind saying that it, the ground, involves a push of the
ground forward on her.
100 I: Okay. And on this scale right here, what sense rating would you
give?
101 S: Mm hm hm. Three, okay.
102 I: Okay.
103 S: "In this and all other cases, it really makes no difference which
force you call the action or the reaction, because they occur
at exactly the same time. The action does not "cause" the
reaction. If the earth could not "push back" on her feet, the
athlete would not push on the earth in the first place.
104 Instead, she would slide around as on slippery ice. Action and
reaction coexist. You cannot have one without the other. Most
important, the two forces are not acting in the same body. In a
way, they are like debt and credit. One is impossible without
the other; they are equally large but of opposite sign, they
105 happen to two different objects." So, let me read this one more
time to myself. --(10 secs.)-- Okay, it makes no difference
which one you call reaction or, reaction or action, as long as

one happens with the other, that's what you're set with. That is correct, as long as there's a one with the other. Like they
106 use debt and credit, you can't have debt without credit. I take it you can't have a reaction without a starting action. It just isn't a civil war, a reactionary movement against the civil war, you know, they're fighting for peace and the reaction movement says 'No we don't want peace now, we want to be back where we started.'

107 I: Can you say in your own words what this paragraph is trying to argue?

108 S: Yeah. It doesn't make one bit of difference, whatsoever, what or, what is labeled the ac, ah, the action or the reaction, what is the action or the reaction. As long as you have both and you know that one happens for the other, then you're all set. Okay, that's, then it works.

109 I: Okay.

110 S: "Newton wrote: "Whatever draws or possesses, ah.. presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone." This statement suggests that forces always arise as a result of mutual actions ("interactions") between objects. If object A
111 pushes or pulls on B, then at the same time object B pushes or pulls with precisely equal force on A. These paired pulls and pushes are always equal in magnitude, opposite in direction, and on two different objects." That I understand perfectly. You push the pen to a paper, the paper is pushing just as much on the pen as you are down on the paper.

112 I: Can you say in your own words what this paragraph is trying to argue?

113 S: Ah, yes, I can. It argues that every time, whenever something is pushed or acted upon by, I don't know, with your finger, by, I mean the leg of that camera stand, for all the pressure it puts on the ground the ground or the floor puts that much pressure on the leg itself. It's almost like in, like it's in equilibrium almost where the pressure's the same from, for the floor and for the chair.

114 I: Does it make sense to you that the stone would push back on the finger?

115 S: Um, not a lot of sense. I mean, I could figure, granted, your finger bends and you can feel the stone on your hand. Um, it doesn't make a lot of sense to me that it pushes back. I only see things that don't move, I miss, I have a lot of trouble with this, I have to admit that I only see things that don't
116 move as not exerting a force, a counter force, or an interactive force as they're calling it, but more as a resisting force. Maybe that's where I've had the trouble throughout the rest of this.

117 I: And let me ask, um, how much sense it makes to you that the stone would push back on the finger?

118 S: Mmmm. Three.

119 I: Okay. Okay.

120 S: "Every day you see hundreds of examples of this law at work. A boat is propelled by the water that pushes forward on the oar while the oar pushes back on the water. A car is set in motion by the push of the ground on the tires as they push back on the ground; when friction is not sufficient, the push on the tires
121 cannot start the car forward." So, what about it? I mean it's just making a statement, an example of what we were just talking about, in this separate paragraph there.
122 I: What are you referring to?
123 S: This and this, these are just examples of this.
124 I: Oh it's like repeating a paragraph?
125 S: Yeah.
126 I: Uh huh.
127 S: This makes somewhat sense to me. I'd say between 3 and 4, like 3.5, if there was one. Um, I can understand that ah, the oar and the water, pushing yourself forward with the water going against the oar. Um, and I also understand, now I'm getting more of the gist of the tires on the ground, the ground pushing back. And you're going forward in the car.
128 I: Hi. [Interruption in interviewing room]
129 S: Though it's um, um, I haven't fully grasped all the friction, ah, when the friction is not sufficient to push on the tires cannot start forward. The friction must be resistance which is what I've been talking about for the last ten minutes incorrectly.
130 I: Can you say in your own words what this paragraph is trying to argue?
131 S: Yeah. Can you give me a second?
132 I: Sure.
133 S: --(14 secs)-- For every force forward, there's a counter force pushing you that way. For every time you row the oars back and propel yourself through the water, the water is going so that, it's going against you and you have to actually move the boat with your hands.
134 I: Okay, let me ask for each of these examples of the third law, the rowboat and the car, could you say if it makes sense to you, and give a sense rating?
135 S: Ah, the rowboat makes probably quite a bit of sense.
136 I: Okay.
137 S: I understand because of the water currents. Ah, the tires make some sense to me, but I haven't fully understood the friction not sufficient yet, but I'll get a better understanding of that, any second now.
138 I: Okay.
139 S: Go?
140 I: Sure.
141 S: "When acceler.. While accelerating a bullet forward, a rifle experiences a recoil, or a kick. A balloon shoots forward while the air spurts out from it in the opposite direction. Many such effects are not easily observed. For example, when an apple falls, pulled down by its attraction to the earth, i.e., its

142 weight, the earth, in turn, accelerates upward slightly, pulled
up by the attraction of the earth to the apple." Hm. So what
should I say about this? Do you want to know if I understand
it?
143 I: Ahh, just whatever your thoughts are.
144 S: I understand the balloon and the bullet because I understand
propulsion more or less. And I get a better grasp of
propulsion than I do friction, and there's a force pushing
out, there's the wind resistance and using, exerting more
force behind it passes, surpasses, it overcomes the wind
resistance. It just continues to go straight.
145 I: Can you say in your own words what this paragraph is trying to
argue?
146 S: Ah, let me see. --(15 secs)-- Ah, nope, no, for the one reason
that I don't see that it's trying to argue anything, it's just
stating facts. That when a bullet is shot forward, a rifle
experiences a recoil and the bullet still continues going
forward. When a balloon shoots forward while the air spurts out
147 of it backwards in the opposite direction, propulsion, it
continues to go straight and overcome the wind resistance till
the 'fuel,' if you will, inside the balloon um, is brought down.
I can't see that it's arguing a whole lot. I'd say that it's
stating facts of examples.
148 I: Okay. For each of these examples of the Third Law, the rifle,
the balloon, and the apple, could you say if it makes sense to
you?
149 S: Yeah. The bullet makes quite a bit of sense to me and the
balloon makes quite a bit of sense to me, but the apple is kind
of like in here, almost towards 3 but not quite as much.
150 I: Uh huh.
151 S: 2.75.
152 I: And could you say a little bit about what's behind your sense
ratings for each of those?
153 S: Yeah, when I'm, I was thinking for the balloon and the rifle
overcoming wind resistance by propulsion. And it's, they're
not really an effect of gravity until they slow down much more,
because then they'll be pulled to the ground but right now as it
goes, they're travelling horizontal with the ground. The apple,
154 in turn, I, I understand why it falls, because of gravity, but I
can't understand the Earth accelerating upward 'slightly' ah,
pulled by the attraction of the apple to the earth. Um, so
those are my things behind the 'senses,' how it makes sense to
me.
155 I: Okay. And let me ask, um, did the examples in the last two
paragraphs um, make the statement 'For every force there is an
equal and opposite force,' understandable and believable.
156 S: Um, understandable, not quite as believable yet, but I, I'm
trying to formulate that in my mind. I, um, for me it's
difficult to get a grasp of that. In fact, I'm going to read
something on it as soon as I leave here. Um, but ah, they do
illustrate the first half of your sentence, the second half I'm

not quite as, you know, I'm not very sure of.
157 I: What are you referring to the first half?
158 S: You said there's, you know, the sentence 'is it totally
believable and understandable.' Believable, yes. I believe
that it would happen. The examples illustrate that it happens,
that it takes place. But it's hard for me to believe that
there's actually a counter-force for pushing on a rock, the
rock's pushing back exactly the same way. The apple dropping on
the ground and the ground is going closer towards the apple.
159 I: Okay. And so for this scale here, could you just say how
160 S: Understandable? 4. Maybe 4.5.
161 I: Understandable? Okay.
162 S: And believable, about 3, maybe 3 and a quarter.
163 I: Okay. Okay.
164 S: Okay. "To summarize, many people say the table is not exerting
a force upward on the book. However, the book is exerting a
force downward on the table because of weight. Therefore,
because of Newton's third law, the table is exerting an equal
force upward on the book." ---
165 I: What are you thinking?
166 S: I'm thinking that it's good that more people think that the book
is exerting a force downward because of its weight. I think
that that's why I started, ah, that was my logic in the
beginning. Um, you know, Newton's Law is a little difficult
for me to grasp but, putting up an equal force backward on the
167 book, you know, resisting a force on the book. I'm glad to see
that many people say that the table is exerting a force upward
on the book, because that is exactly what I said, that it's
not exerting a force upward on the book, is exactly what I said.
168 I: Is the explanation on this page, this entire page,
understandable and believable to you?
169 S: Believable, no, because I've always had trouble with anything
with physics. I'm more of a literature, literary-type person.
Where, you can talk about it, and science is great, but it has
its own place somewhere else. Um, I'm not really much a fan of
physics, and I tend to stay away from it as much as I can. I
170 mean I read a little bit on it. But, understandable, yes, I
understand it. I understand how it can happen, why it happens.
But, believable, I just find that, you know, how can, I don't
see the logical arguments that, that the ground is actually
making a force propelling the girl forward while she steps back.
171 Um, so far, they've just told me stuff, they've given me
examples of how it happens, and why it happens. But, um, those
aren't really sufficient, without knowing any of the formulas of
how it comes about, or if there is actually this force, or it's
just a theory.
172 I: Okay.
173 S: Maybe I'm doubting one of the biggest philosophers of all time,
Newton, but he has been wrong before about the counter force,
the force inside a vacuum, that says two things don't fall at
the same rate. The New York Times published an article about

that. So, to say that this is exactly right and exactly
174 correct, stands to reason, ah, more or less, you know, give or
take situations. Maybe it's exactly correct or maybe it's
exactly wrong. I understand it but it's not at all wholly
believable.

175 I: Okay, and let me ask, um, does the explanation on this page help the idea of an upward force from the table, make sense?

176 S: No, no it does not.

177 I: And let me, here's another scale if you could just rate how much um, the explanation helps, the idea of a force to make sense, on that scale from one to five.

178 S: Okay, it helps a good amount to make sense. It helps me to
understand, you know, how it happens, the actual, the actual
actions that make it happen, the step down on the ground, the
rowing of the oars, the shooting of the bullet. It helped me
to, that made sense in my mind how that happens. But it, on
179 the same turn I'd have to put it down lower because I don't
fully believe all the stuff that it's saying. I don't believe
that those are the principles that make the car go, that that is
why the rock is pushing exactly the same amount back on the
finger. Maybe it is but ----

180 I: Okay. And let me ask um, which examples on this page helped the idea of an upward force from the table make sense, and which did not help?

181 S: Well the apple falling didn't make sense. That did not help the upward force. The rowing did. And the rock and the finger somewhat. More no than yes, but it gave me a little, like a vague outline of why it happens. Those are probably the three predominant ones.

182 I: What about ah, the runner.

183 S: The runner I've had a difficult time getting to understand,
getting a grasp on the forward feet, and backward movement, and
the push on the ground, and et cetera, that type of thing, you
know, the pushing her feet back against the ground involves a
push of the ground forward on her just seems odd to me, that I
184 just haven't been able to understand that quite as well. And
that may be one of the better examples to help me understand
this statement here but I've had trouble right, dealing with
that one, because

185 I: Which statement were you referring to?

186 S: This one, you know, for every, you know every, ah one force another, and then the other force, exerts a force on the first.

187 I: Okay.

188 S: You know, one force is her foot on the ground and the other is the ground on her foot.

189 I: Okay. Ah, let me see, what about the car?

190 S: The car was okay, until it had this little, little section here about when friction is not sufficient, the push on the tires cannot start the car forward. Um, then, that's the first time that word popped up in the entire thing, I mean, out of these last 8, 9 sheets they've only used the word friction once. And

191 I'm assuming that's resistance to the tires spinning on the ground. But before that there wasn't any resistance. On the girl, they don't talk anything about friction, they don't talk about that in the gun, they don't talk about it in the rock. Um, so I guess I, what have I not done, I did the gun.
192 I: Did ah, I don't remember you saying anything about the gun or the balloon.
193 S: Okay. Ah, they did in the way that I understood more about propulsion and how they go forward, because I understand that they'll eventually come to the ground. That the force of the air pushing on them, and more force pushing forward, they propel forward just by the wind splitting when they're passing,
194 almost like a plane flying through the air. Um, I understand the action and reaction there. I mean, without any resistance, the bullet won't go anywhere. I mean it would be shot out of the thing and shot into a huge room, a vacuum, the bullet would go on its propulsion, and there'd be no resistance against it,
195 it would just continue, and continue to fly, continue to fly. And the same with the balloon released into a vacuum type situation. Once the exhaustion of the air inside was out, it wouldn't do anything. ---- That's a 5, 6, 7.
196 I: So did the gun and balloon help?
197 S: Yeah, in, yes, yeah.
198 I: Okay. Okay, do you have any other thoughts or comments before we move on?
199 S: Um, no, I think I'm doing okay.
200 I: Okay.
201 S: Holding my own.
I: Okay. And what I'm going to do now is, um, ask you the same three questions that I asked at the beginning. Um, and then I'm going to ask you a couple more questions that you haven't seen before. So start off with these.
202 S: Go for it.
203 I: If you could just respond to that again.
204 S: "A book is at rest on a table. Which of the following do you think is true?" The only thing is if I answer this, I know, said that Newton's Law says that it does. But, okay they want what I think. I still think that it doesn't. And I'm pretty confident about that. And why I don't think it does is because
205 I haven't been given enough evidence to prove that it actually does. I mean, I can only handle so much physics-type things. You know, gravity is about the extent of my physics mind. And to say that there's forces beyond thinking, beyond, you know any control of the human being, um, pushing up on a book, or even
206 the book pushing down on the desk, are odd. The only reason I know that the book is pushing down on the desk is because gravity is a real force, it's a magnetic force. You know out in space where it's out, right outside of the magnet, the book would stay right in mid-space and would not fall. That's why.
207 I: Okay. And, let me
208 S: That's fairly confident.

209 I: Okay, and let me ask, um
210 S: Does it make sense?
211 I: Yeah, for each of these, each of these statements, if you could just say how much sense each makes to you.
212 S: Ah, some, for this, this first one, I can understand why it happens. You know, I can understand because they say that for every action there's a reaction and that, I understand that and that makes sense to me. But this makes more sense to me that it does not, because, you know, granted, it can be wrong. Okay, it
213 is not, there's, saying an absolute, always happens kind of thing, it's difficult to say. So I'd be more confident about it, like 4, for the bottom, and 3 for the top.
214 I: Okay. Here's the next one.
215 S: Ah, the goat. "A stubborn goat is pushing against a wall. While the goat is pushing, does the wall exert a force back on the goat. Yes, or No." Let's see. Ah. --(14 secs)-- Nope. I'm still fairly confident about that. Do I have to explain it? Does it say it wants me to explain it, because of the same
216 reason in the fly sitting on the Washington Monument, and the same reason the book sitting on the table. I, I have a hard time grasping that this is pushing as, just as much on this as he is on that.
217 I: Okay.
218 S: That's why. I'm very confident, and does it make sense? The first part, yes, it makes some sense to me, because I'm starting to get the idea of the wall having the same amount of resistance as the goat pushing in. And, no, is kind of like in between. I'm starting to shade away from, like 3.5.
219 I: Okay.
220 S: Three and a half. Because seeing better and better examples of things pushing on each other like this goat on the wall is a lot better example than the book on the table, in my perspective I see it as a better example. And ah, it makes me a little less sure that this isn't responding to this.
221 I: Okay, and here's the next one.
222 S: 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, or whether the monument exerts a force on the mosquito while it is resting there." While the mosquito is resting there does the monument exert an upward
223 force on the mosquito? --(10 secs)-- Mm, about right there. This, because I've just started to get the understanding now, more when I came in here I was more or less ah, not ignorant but not really fully understanding of science and physics as a force type thing. I haven't really studied or read about it at all.
224 Getting better and better example of, reading that full page gave me a little better example of forces. To say that it is still, though, is a little tough for me to say the Washington Monument is exerting an upward force on the mosquito. But I can understand the mosquito putting a downward force on the monument. So I said that, I said no there, and I'd say about

there.
225 I: Okay, and for each of your answers could you say how much sense it makes to you?
226 S: How much sense 'no' makes to me? This one.
227 I: Three?
228 S: Mm hmm.
229 I: Okay.
230 S: And for the second 'no?' That makes quite a bit of sense to me that it would make, that it would exert a force on the monument.
231 I: Okay. Okay, thanks. And um, I've just got a couple more questions. This one that you haven't seen before, if you could just read that and respond to it.
242 S: Okay. "A box weighing 50 lbs. rests on top of another box weighing 100 lbs. Think about whether the upper box exerts a force on the lower box and whether the ground exerts a force on the lower box." Does the ground exert an upward force on the lower box? Mm jeez, you make these hard on purpose, huh?
243 Okay, I guess I'm going to have to start saying 'yes,' because I'm starting to understand this a little better. --(30 secs)-- So if I said yes I have to chose one of these four, huh?
244 I: Okay.
245 S: B. There. The reason I turned my answer 'yes' is totally hypocritical of all the other things I've been saying, is that I'm starting to get a better understanding of, of the different forces in between here. You know the one between the 50 and 100, the one between the ground and that hundred box. Um, I'm
246 still not too sure, and I don't abandon my idea that Newton isn't the absolute right. It could very well be that just the boxes are pushing down on the earth, this one on this, and this on this, and these two together on the earth. Um, but I've changed to yes because I think that there is something, and now
247 that it's being said to me in weight, I hadn't really been thinking about pressures and weight, you know, not pressures, but forces and weight. It being set in weight changes a little bit of the aspect of how I look at it. Ah, as I can honestly say, I didn't think of the weight as the mosquito, I didn't
248 think of the weight of the goat, or the push of the goat, and I didn't think of the weight of the book.
249 I: How does that change things?
250 S: Um, it just, I don't know, in my mind it gives me a better, something more solid. Weight seems to be one of the few things that I can, that I understand. Um, and using actual numbers, ah, puts me on a little firmer ground, although I'm still not certain, so I wrote 'not very confident' and in the little book 'not very confident.'
251 I: Okay.
252 S: Sense
253 I: And, oh, could you say a little bit about your
254 S: Oh, this one.
255 I: Yeah, your second answer.

256 S: Okay. I said 'yes,' that for both the ground and the upper box exert force on the lower box, but the ground exerts a larger force. There's more area, well, maybe I should change this to this. Yeah, I changed it to 'C,' is that okay?
257 I: Sure.
258 S: Okay, um, ah, because the ground in this little area is exerting a force up on that, and the 50, the box on the top is really pissing me off. This is not, let's see, this box is smaller, the lower box but the ground exerts a larger one. The lower box put the upper box, is it larger, or is it smaller. Okay, I'm
259 going to, this might not be right but, what I was looking for is, the top one is less and the bottom one is more. Is that what I had? The top one is less and the bottom one is more. That was the one I had there. Do you mind if I change this? Oh, that's wonderful!
260 I: Sure, whatever you want to do.
261 S: Because there's more area on the bottom of this box. There's more force pushed up on it. This bottom, the little base is faced right here. More force is being pushed on it, as in, not as much force is being pushed on these little separate sections of this box by this 50 smaller box. Um, that's why I said 'yes,' see how sure I was.
262 I: And, is your confidence the
263 S: Ah, not, not a whole lot, because I'm just starting to get the understanding about counter force and force, ah, so I'm not really sure that that's right but
264 I: Okay. And, yeah, let me ask how much sense each of your answers makes.
265 S: Um, this one I'd have to put it right there. You don't mind me writing on this paper?
266 I: No, that's fine.
267 S: This one I'd have to put about right there, just a little
268 I: Your first answer?
269 S: Yeah.
270 I: Okay.
271 S: And my second one would be more towards there, put it about there, 3.75 or so.
272 I: Okay. Okay, okay and here's the last one.
273 S: Oh no another block prob, Wait, I knew that made a difference! Okay.
274 I: If you'd just read that out loud.
275 S: Oh, sorry. "A large steel block weighing 2, ah, 200 lbs rests on a small steel block weighing 40 lbs. as shown below. Think about whether A exerts force on B, and whether B exerts a force on A." And I have to say 'yes,' because weights are starting to make me feel more comfortable. This, so I'd have to say I'm
276 more towards 'fairly confident.' And I'm getting a better understanding using the numbers, using weights makes me feel more sure about myself, ah, for some unknown reason. Maybe it's, maybe it's just because they're strewn out in front of me. But, um, so I'm more, I'm fairly confident that this box is

277 putting up a resisting force to A which is more on top. If I said 'yes,' A and B, A exerts a larger force. That was, there. I would say that A and B exert a force on each other, but A exerts a larger force, more weight, and covers the entire face of this box, with 200 lbs. of pressure which is 160 more lbs. pushing down on the box. And I'm more or less confident about that. Right there.
278 I: Okay.
279 S: And, if you want to know sense wise, I'd think that these are maybe 3 and about 4. This would be 3 and this would be 4.
280 I: For your second answer?
281 S: Yeah, the second answer would be 4, because it's making more sense to me that, that ah, A and B exert a force on each other. but A is better, a larger more heavy box so exerting a larger force.
282 I: Okay. Okay, thank you very much.
283 S: Okay.
284 I: That's all I've got!
285 S: Alright. A lot more difficult than I thought it would be.

APPENDIX C

EXPERIMENTAL CASE STUDY TRANSCRIPT

TRANSCRIPT

Cognitive Processes Research Group
University of Massachusetts

Name: John (not his real name)
Problem: Experimental Explanation
Interviewer: D. Brown

001 S: "Since the rest of the exercise will deal with the idea of force, force is defined below. A force is a push or a pull of one object on another object."
002 I: How does that sound?
003 S: Sounds alright.
004 I: Ok. Ok, great, let's put this over here then. Ok, here's the first problem, if you could just read that out loud and respond to it.
005 S: "A book is at rest on a table. Which of the following do you think is true? The table exerts a force upward on the book," false. "The table does not exert a force upward on the table, on the book." Do you want me to write on this?
006 I: Yeah, sure.
007 S: The table does not exert an upward force on the book. True.
008 I: Ok, and
009 S: Do you want me to do it by this?
010 I: Yeah, this is a confidence rating which will probably be on every question, and it's just sort of a continuous line, just put an X wherever you, wherever your confidence lies. So if you're sure then you'd put an X over that, or if you're fairly confident or halfway in between, or not very confident.
011 S: Yeah, I'll mark off this. I'm never absolutely totally sure.
012 I: Ok.
013 S: "Please explain why you think the table exerts or does not exert a force up on the book." Hmm. I, can't explain it, it's common sense I guess, cause my hand's above the book, above the table right now and it's not exerting any force. Do you know what I mean? I mean it's hard to explain why, but I, my hand's on the
014 table right now and it's not exerting any force upward on my hand.
015 I: The table?
016 S: Yeah.
017 I: Uh huh.
018 S: You know, I guess gravity would be good.
019 I: Gravity?
020 S: Well, I don't know, it's hard, please explain why I think. Experience I guess. It's hard to explain why, do you know what I mean? Because I've had things on tables for my whole life,

and it's never exerted force upward onto
021 I: Uh huh.
022 S: I don't know how scientific that is, how scientifically, you
know, this just goes
023 I: Yeah, just, you know, the more you can say what you're thinking.
024 S: So what do you want me to write for that?
025 I: You don't need to write anything for that, that's just, you
know, you can answer that verbally. Ok. Here's something a
little different. Um, if you could just read that.
026 S: Do you want me to read it out loud?
027 I: Sure.
028 S: "Throughout our lives, we have had a wealth of experience with
the physical world which leads us to feel that some things make
sense and other things don't. A statement makes sense when we
understand it at an intuition, intui, intuitive or gut level.
There are times when we know an answer is correct, (that is we
029 are very confident in our answer) but it doesn't really make
sense. For example, many people are confident that if a person
throws a boomerang, it will circle around and come back. But it
doesn't make sense to them that it should come back. What makes
sense to them is that the boomerang should just go in a straight
030 line. At other times, we are confident about an answer, and it
makes perfect sense. For example, if a large truck runs into a
small car, most people are confident that the car will get
damaged. It also makes sense to them that the car would be
damaged. For the question the interviewer shows you, please
031 rate how much sense each answer makes using the following, using
the scale below. (Note: When you give your ratings, please rate
how much sense each answer makes, not how confident you are that
the answer is correct.)"
032 I: Ok, let me ask, in your own words, um, could you say what the
difference is between being confident about an answer and the
answer making sense?
033 S: Being confident is knowing the correct answer. I mean it's like
if you take a test, and you get someone else's test and you
memorize the answers, you're confident they're the right
answers, but you might not know why they're the right answers.
034 I: Mm hmm. Ok
035 S: It's, maybe, knowing the answer, but not knowing why the answer
is this.
036 I: Uh huh. Yeah and going back to say, the boomerang example, you
know, some, I don't know about yourself, but some people, you
know, they know that it, they see somebody, it circles around
and comes back, so they know that that's right, but it doesn't
make sense to them at all that that would happen.
037 S: Yeah.
038 I: So, so that's just to try to differentiate between making sense
and confidence. Um, ok, so, just looking again at this problem,
um, if you could just, using this scale here, the one to five
scale, if you could just rate um, how much sense your answer
makes.

039 S: It makes perfect sense.
040 I: Ok, so that would make a five. And how much sense does the other, the one that you didn't answer, how much sense does that make?
041 S: The one that I didn't answer?
042 I: Yeah.
043 S: I answered both of them.
044 I: Uh, well the one that you said was false.
045 S: That makes sense to me also.
046 I: It makes sense to you?
047 S: Yeah.
048 I: How much sense?
049 S: It makes perfect sense to me.
050 I: Ok, so both of them make perfect sense to you?
051 S: Yeah, because if I'm saying the table does not exert an upward force, I'm also answering this question here.
052 I: Uh, ok, oh right, ok, how much sense does it make to you that the table exerts a force upward on the book?
053 S: Makes no sense to me.
054 I: Ok.
055 S: I'll give it a one.
056 I: Ok, great. Um, put this over here. Ok, here's the next one, if you could just read that
057 S: "A stubborn goat is pushing against the wall. While the goat's pushing, does the wall exert a force back on the goat?" Is there a force back on the goat?...
058 I: What are you thinking?
059 S: Well, I thought for a second that I remembered somewhere in my science years that the wall would exert a force back, but I forget when. So, umm, I'm just answering no and put not very confident.
060 I: Ok. Ok, and this is, for if you answered yes, so you don't need to answer that. Um, could you say why you answered that?
061 S: Well, I, for a second I thought I remembered somewhere in, when I was taught, my science years, that uh, the wall would exert a force back, but I forget where I heard that.
062 I: Ok, why did you give the answer that you did?
063 S: Because of the answer that I gave there, might as well be consistent.
064 I: Uh huh.
065 S: I mean if it's going to exert a force back here it will exert a force back there.
066 I: Ok. Ok, and let me um, let me ask you again if you could just say how much sense your answer makes to you, how much sense does it make that it doesn't exert a force, the one that you answered.
067 I: Ok. And how much sense that it does?
068 S: How much sense that it?
069 I: How much sense does it make that it does exert a force.
070 S: Makes no sense.
071 I: Ok. Ok, great. Here's the next one. If you could just read

that and answer it.
072 S: "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. While the mosquito is resting there, does the monument exert an upward force on the
073 the mosquito?" No, I don't think so. I'm fairly confident about that.
074 I: Ok.
075 S: "If you said no, the mosquito exerts a force on the monument." Yes, I'm fairly confident.
076 I: Ok. Ok, and let me again ask you if you could rate how much sense each of your answers makes, the ones that you checked.
077 S: They both make perfect sense.
078 I: Ok. Ok, great. Thanks. Ok, what I'm going to do now is give you an explanation about the book on the table situation
079 S: Mm hmm
080 I: And I'm going to ask you along the way about how understandable it is.
081 S: Right.
082 I: Um, at the end I'm going to ask you how understandable the explanation is as a whole.
083 S: Alright.
084 I: Ok, so if you could just read that. After, at each break, after each paragraph I'll just ask you a couple questions.
085 S: "In this exercise we will consider the question of whether a table pushes up on a book resting on it. Consider pushing down on a spring with your hand."
086 I: What are you thinking?
087 S: I don't see what pushing down on a spring with your hand has to do with putting a book on the table.
088 I: Does it make sense to you that the spring would push up on your hand?
089 S: Oh yeah. It would put pressure on your hand.
090 I: OK. How much sense does it make that the spring would push up on your hand?
091 S: Makes perfect sense.
092 I: OK. Umm, is this different from the book on the table?
093 S: The spring on the hand?
094 I: Yeah.
095 S: Yeah, I think so.
096 I: How so?
097 S: Because the table isn't forcing your hand up, and you don't have to put any pressure on the table so your hand doesn't come back up. With the spring you have to put some pressure on the spring so it doesn't push your hand up. Do you know what I mean?
098 I: I'm not quite sure I...
099 S: Well, you're talking about pressing down on the spring, right?
100 I: Right.
101 S: If you press down on the spring there's some pressure from the

spring to push your hand back up.
102 I: Uh huh
103 S: Put your hand on the table there's no pressure whatsoever
pushing your hand back up
104 I: OK
105 S: "Now consider the case of a heavy dictionary being placed on a
bedspring so the spring compresses some."
106 I: What are you thinking?
107 S: It's just, um, explaining something, I don't know what the
paragraphs that do anything..
108 I: Does it make sense to you that the bedspring pushes up on the
book?
109 S: Yes
110 I: How much sense
111 S: Perfect
112 I: perfect sense. Ok, could you explain why it makes sense?
113 S: For the same reason when you put your hand on it.
114 I: OK. Ok, go ahead.
115 S: "When the book is placed on the spring, the spring compresses.
The further down the spring is pushed, the more it pushes back.
The spring is compressed by the book to the point where it
pushes back with a force equal to the book's weight. For
example, if the book weighs 10 pounds, the spring compresses
116 until it exerts an equal upward force of 10 pounds. In a
similar way, if you hold a 30 pound dictionary in your
outstretched hand, you will have to exert an upward force of 30
pounds to hold it there."
117 I: What are you thinking?
118 S: Makes sense....
119 I: Does it make sense to you that the spring would exert a force of
10 pounds up on a book weighing 10 pounds?
120 S: It makes sense to me. Makes some sense
121 I: Some sense, so, on a scale of sense
122 S: Three. Makes some sense
123 I: Ok. Is this different from the book on the table?
124 S: Is what different?
125 I: The book on the spring.
126 S: Yeah, it's different from the book on the table.
127 I: Ok. Ok, go ahead.
128 S: "Many people say the book on the spring is different than the
book on the table. They say that although neither is alive, the
spring compresses but the table is rigid. But is the table
rigid? Imagine a flexible board between two sawhorses. If you
were to push down on this board it would bend and push back,
129 just like pushing down on the spring. The board would also push
back on a book, just like the spring. Now imagine thicker and
thicker boards."
130 I: What are you thinking?
131 S: Starting to make some sense...can't imagine this bending any for
a book, to press back on it.
132 I: Does it make sense to you that the flexible board pushes up on

the book?
133 S: Pushes up on it?
134 I: Yeah.
135 S: Yeah...
136 I: How much sense?
137 S: Makes perfect sense.
138 I: What would happen if the board got thicker and thicker?
139 S: Umm, it would bend less and less..guess the pressure would become less and less too.
140 I: Is the book on the board situation different from the book on the table?
141 S: Ummm, I guess so, I mean, amount of pressure.......do you want me to keep reading?
142 I: What are you thinking?
143 S: I'm thinking it's starting to make some sense.
144 I: How so?
145 S: Well, that the flexible board bends, and if you just, if there, the board's gonna bend less and less, I guess there'd be some pressure back..
146 I: Ok, go ahead.
147 S: "If you had a thick enough board, it would just be like a table. Both the board and the table would bend a teeny, teeny bit under the weight of a book. Another way to think of the table is like very stiff foam rubber. Even though the stiff foam rubber would not compress much under the weight of the book, it would compress some."
148 I: What are you thinking?
149 S: Starting to understand a little bit...
150 I: Does it make sense to you that the foam rubber pushes up on the book?
151 S: (Whispers - Foam rubber pushes up on the book) Yeah, makes sense, horse sense. Isn't that foam rubber, that's not styrofoam, we're not thinking about styrofoam, we're thinking about rubber, foam rubber
152 I: Yeah
153 S: That makes sense. Makes perfect sense
154 I: Makes perfect sense. Is the book on the stiff foam rubber situation different from the book on the table?.....
155 S: Umm...uhhh, no I guess not
156 I: What are you thinking?
157 S: I was just thinking about the different materials
158 I: Different materials?
159 S: Of the rubber and the table. I guess it would make a difference
160 I: What were you thinking about them?
161 S: Well, it would be a difference in the pressure exerted back, but...
162 I: Ok, go ahead
163 S: "The table is composed of molecules which are connected to other molecules by bonds which are springy. Thus the table has some amount of give or bendiness or squishiness to it. If you were to look closely with microscopes you would see that the book

causes a slight depression in the table. The table, just like
164 the spring, the flexible board, or foam rubber, is bent or
compressed some and thus pushes back. Like the spring holding
the dictionary, the table bends or compresses just enough to
provide an upward force equal to the book's weight."
165 I: What are you thinking?...
166 S: I'm thinking I knew I read this somewhere. It's like with the
goat thing..well, actually, yeah I think I remember this..
167 I: What are you thinking?
168 S: I thought, yeah, I think I remember that, yes. This, this makes
sense. It doesn't make perfect sense cause I don't have a
scientific type of mind, but I guess explained like this it
makes sense..
169 I: Is the table deformable or squishy at all?
170 S: Squishy? The table's not squishy
171 I: Or deformable?
172 S: Well, it's deformable. You could deform it.
173 I: Ok, go ahead.
174 S: "To summarize, many people do not think the table can exert a
force since it is rigid and lifeless. However they feel a
spring can exert a force if a force is exerted on it because it
wants to get back to its original shape. Thus there seems to be
a distinction between rigid objects and springy objects.
175 However, if you look closely enough at a table it is springy
because of its molecular makeup. Because of this springy nature
of all matter, the table can and does exert a force back -
upward on the book. Just like a spring, the table compresses
(on a microscopic scale) until it is compressed enough to
provide an upward force equal to the book's weight."
176 I: What are you thinking?
177 S: Makes sense the way this is explained.
178 I: Is the explanation on this page understandable and believable to
you?
179 S: Yes
180 I: Let me ask, um, this is another scale, um, which, where you can
rate how understandable and believable the explanation is
181 S: Very believable
182 I: So, a 4?
183 S: Yeah
184 I: Ok. Ok, um, do you want to comment on that at all?
185 S: I don't think anything's completely believable, so I wouldn't
give it a 5.
186 I: Uh huh. Ok. Does the explanation on this page help the idea of
an upward force from the table make sense?
187 S: Yes
188 I: Ok, let me ask, um, here's another scale which asks how much
does it help to make the idea of an upward force from the table
make sense.
189 S: Four
190 I: Four, ok. Ok, let me ask you, which examples on this page
helped the idea of an upward force from the table make sense and

which did not help?..
191 S: I don't think the spr.., well, I guess I didn't think the spring helped, but in context I guess..out of context you just compare the spring and the table it wouldn't help, but you sort of built a way up from the spring, which is obvious, to a flexible board, to a not so flexible board, to foam rubber, to a table, which is pretty good. So I wouldn't think there's anything in here...
192 I: Were there any examples that didn't help?
193 S: No, I don't think so.
194 I: Ok, ok, great.
195 S: Wait, actually the heavy dictionary and the bedspring.
196 I: Heavy dictionary on the bedspring?
197 S: Yeah
198 I: How didn't that help?
199 S: Cause it was just plopped in there..I mean cause in the next paragraph you say when a book is placed on a spring the spring compresses.
200 I: Uh huh
201 S: and you don't need this part right here at all.
202 I: That paragraph there. Do you think the, um, ok so but if I took this example of this paragraph out, uh, it would still be talking about a book on a bedspring.
203 S: Yeah, but, you don't need this part right there
204 I: Uh huh. Do you think I still need the book on the bedspring, I mean to at least talk about in this paragraph or take it out of that too?...
205 S: Do I think you don't need this example at all, or do I think that you don't need to say there's a book on a bedspring?
206 I: Yeah, do, do we not need that example at all?
207 S: No, I think that's a good example.
208 I: It's just that one paragraph?
209 S: Yeah, that's just a little (mumbles)
210 I: What did you think when you saw that?
211 S: At first?
212 I: Yeah. When you saw that paragraph. I mean, it sounds like you were saying that..
213 S: At first I was just, I didn't think anything of it, because I was just reading the
214 I: Uh huh
215 S: But then I went back and looked over it and you don't need to say that
216 I: Ok. Great, thank you very much. Ok, um, do you have any other comments or thoughts on that explanation before going on?...Ok, thanks. Ok, what I'm going to do now is just ask you the same three questions I did at the beginning if you could just respond to them again.....
217 S: Put it in the middle there.
218 I: Ok.
219 S: And why do I think. Because I just read that definition, that ex.., all those steps, explained it pretty well.
220 I: How would you explain it in your own words?

221 S: That the molecules compress when, um, pressure's put on 'em, and they exert the same amount of pressure back on, or the same weight, back on whatever's putting pressure on 'em. And when the pressure is relieved, the molecules decompress.
222 I: Ok. And how much sense, um, get the sense scale again, how much sense does it make that the table exerts a force upward on the book?
223 S: Makes quite a bit of sense, four.
224 I: And how much sense does it make that the table does not exert a force upward on the book...
225 S: Umm...., makes some sense..
226 I: So a three
227 S: Yeah
228 I: Ok. Ok, here's the next one. Ok, so this is the goat problem.
229 S: Yes. (mumbles)
230 I: Ok, so which one did you answer?
231 S: The wall exerts a force which is the same size as the goat's force on the wall.
232 I: Ok, um, and let me again ask you how much sense you answer makes, your two answers, how much sense does it make the wall is exerting a force back?
233 S: It makes quite a bit of sense.
234 I: Ok, and how much sense does it make that the wall exerts a force back which is the same size as the goat's force on the wall.
235 S: It makes quite a bit of sense.
236 I: Ok. Ok, could
237 S: Actually it makes a lot of sense, cause if, cause if it exerted more it would cush, push the goat back, and if it exerted less, it would break..That's right isn't it?
238 I: Well, I won't say.
239 S: Well, yeah, that's the way I think about it a little bit.
240 I: So are you, so how much, what rating would you give it?
241 S: Makes, makes, wellll, yeah, I guess it makes perfect sense to me.
242 I: Ok. And could you explain in your own words, um, why you answered the way you did?
243 S: Because if it exerted less it would break, and if it exerted more it would push the goat back.
244 I: Ok. And why did you answer that the wall was exerting a force?
245 S: Because of the thing I read.
246 I: Ok, how would you, how would you explain it in your own words?
247 S: Because the molecules compress, and, um exert the same amount of pressure back on the goat as the goat is making on the wall.
248 I: Ok. Ok, great. Here's the next one.
249 S: (Mumbles).......
250 I: Ok, what answers did you give?
251 S: Um, I gave yes, that while the mosquito is sitting there the monument exerts an upward force on the mosquito. And I said each exerts a force and the forces are the same size.
252 I: Ok. And again, how much sense do each of your answers make?
253 S: They're starting to make perfect sense. They make perfect

sense.
254 I: Both of them?
255 S: Yeah.
256 I: Ok. Once again, could you explain in your own words why you, why you think the monument is exerting a
257 S: Ahhh.
258 I: An upward force on the mosquito?
259 S: Because the, uh, molecules are, uh, they compress, and exert the same force back on the mosquito that the mosquito exerts on the monument.
260 I: Ok. Ok, great. Thanks. Any other comments on this one or thoughts?
261 S: No, pretty much, well, it's hard to imagine a mosquito making any kind of, um, force on the monument which is, uh, pretty hard. Doesn't make much sense. Well it makes a lot of sense, I mean now that it was explained to me. It doesn't make a lot of common sense. Do you know what I mean?
262 I: How are, how are you distinguishing that?
263 S: Well because, from this, I understand that when something, when some pressure's put on something, it compresses, even the littlest amount, and pressure's exerted back. But it's hard to see a mosquito making a little dent, molecular dent. Yeah, a little indent in the monument, just because it landed on it. Not a permanent dent, but..
264 I: Ok. Thanks. Any other, any other thoughts?
265 S: No, I'm all set.
266 I: Ok. Get these out of your way here. Ok, and here's another one that you haven't seen, if you could just read that and respond to it.
267 I: "A box is weighing, a box weighing 50 pounds rests on top of another box weighing 100 pounds. Think about whether the upper box exerts a force on the lower box and whether the ground exerts a force on the lower box. Does the ground exert an upward force?" Yes. "Both the ground and the upper box exert
268 forces on the lower box, but the upper box exerts the larger force. Both the ground and the upper box exert forces on the lower box, but the ground exerts the larger force."
269 I: Ok, what are you, could you explain your answers?
270 S: Well, let's see, the ground exert an upward force on the box because the box is exerting a force on the ground, 100 pounds worth of force and the ground is exerting 100 pounds worth of pressure back on the box.
271 I: Ok
272 S: Both the ground and the upper box exert forces on the lower box, but the ground exerts the larger force because it's exerting 100 pounds worth of pressure whereas the upper box is only exerting 50 pounds.
273 I: Ok. And could you say how much sense each of the answers makes?
274 S: They make perfect sense
275 I: Ok. Ok, and once again could you explain, um, why you answered for both of your answers, why you answered

276 S: In my own words
277 I: Yeah, in your own words, why you answered the way you did.
278 S: Um, the ground, the ground exerts an upward force because a
hundred, actually 150 pounds worth of pressure is on the ground
and compressing the molecules. The molecules are exerting 150
pounds worth of force back. And the ground exerts the larger
force cause it's exerting 150 pounds worth of pressure whereas,
279 um, whereas the higher box is only putting 50 pounds of pressure
on the lower box.
280 I: Ok. Thanks. And here's the last one, if you could just read
that.
281 S: "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 B on A. Does B exert an upward force on
A?" Yes.... "If you said yes, A and B each exert a force on the
other, but A exerts a larger force; each exerts a force but B
exerts a larger force".......
282 I: Ok, could you explain your answers.
283 S: Well B exerts..200 pounds worth of upward pressure on, uh, A,
cause the molecules compress, actually, well actually that
really doesn't make that much sense to me, but I'm putting it
down because of this here.
284 I: Of the explanation?
285 S: Yeah. I don't understand how something that weighs 40 pounds
can exert 200 pounds worth of pressure....
286 I: Ok, so..
287 S: A and B exert a force on each other but A exerts a larger force.
I'm fairly confident about that cause, uh, A weighs more..
288 I: Ok.
289 S: Well, I don't know if I'd say that. I might as well be
consistent. Cause that exerts 200 pounds worth of weight down
on B, that puts 200 pounds back up.
290 I: Could you explain why you changed the way you're thinking?
291 S: Well, I change because I might as well be consistent..with this
292 I: With the explanation?
293 S: Uh huh, because it would put the same amount of pressure back up
on it that's being put down on it.
294 I: B would?
295 S: B would...
296 I: Ok, let me ask for each of the answers that you gave, how much
sense, you know, this scale, how much sense it makes.
297 S: The first one makes perfect sense. The second one makes a
little sense...makes some sense, three.
298 I: Ok. Um...before you said something that it didn't makes sense
to you that something which weighed 40 pounds could exert 200
pounds
299 S: Worth of pressure?
300 I: Yeah. What were you thinking there?
301 S: I don't know. I, just that, it doesn't make sense that 40
pounds could exert 200 pounds worth of pressure
302 I: Uh huh.

303 S: Yeah.
304 I: Could you say why?
305 S: Cause it weighs 40 pounds
306 I: Uh huh
307 S: Yeah. Well, B if it weighs 40 pounds.
308 I: Ok.
309 S: And I know that's not true, I know it can, but it just doesn't make sense to me.
310 I: Ok.

APPENDIX D

WRITTEN STUDY INSTRUMENT

This appendix contains the following:

1) Instructions for part I.
2) Page explaining sense scores.
3) Instructions for part II.
4) Experimental explanations. (Note: the parts of this explanation which were not included in the bridging alone explanation are in brackets. The diagram of the molecules connected by springy bonds was also not included.)
5) Control explanation.
6) Post questions. (Note: Except for one question, the Runner Problem, the questions asked were identical to the questions in the interviews (see appendix A). The order of the questions was as follows: pre-questions - Goat Problem and Table Problem; post-questions - Table Problem, Goat Problem, Runner Problem, Two Boxes Problem, and Steel Blocks Problem. Only the Runner Problem is reproduced in this appendix.)

Instructions

This questionnaire is divided into two parts. After answering the questions in the first part, please come forward to get the second part.

On each question you will be asked to say how sure you are of your answer. For instance, if the question were:

When you drop a silver dollar it will:

___1) Fall to the ground
___2) Rise into the sky
___3) Float in midair

You would probably mark (1) and be absolutely sure. In this case you would mark the confidence scale like this:

0	1	2	X
Just a blind guess	Not very confident	Fairly confident	I'm sure I'm right

However, if you weren't too sure about a question, you might mark:

0	X	2	3
Just a blind guess	Not very confident	Fairly confident	I'm sure I'm right

or

0	1 X	2	3
Just a blind guess	Not very confident	Fairly confident	I'm sure I'm right

If you have no idea about a question, take a guess and mark:

X	1	2	3
Just a blind guess	Not very confident	Fairly confident	I'm sure I'm right

Whenever you are asked to explain your thoughts, please respond by writing a sentence (or two or three) which summarizes your thoughts as clearly as possible. The purpose of this research is to explore ways students think about situations in the physical world. This will help in designing science instruction students can understand more easily. The more clearly you can explain your thoughts the more it will help us toward this end.

When you are going through this questionnaire, please do not look ahead to upcoming pages. Move on to the next page only when finished with the current page. Also, please do not change answers or add or erase anything on previous pages. It is important for the research that your answers show what you are thinking at each point, rather than what you might think later on after going through more of the questionnaire.

Thank you.

DEFINITION OF FORCE

Since the rest of this exercise will deal with the idea of force, force is defined below.

A force is a push or a pull of one object on another object.

WHAT MAKES SENSE?

Throughout our lives, we have had a wealth of experience with the physical world which leads us to feel that some things make sense and other things don't. A statement makes sense when we understand it at an intuitive or "gut" level.

There are times when we are confident about an answer, and it makes perfect sense. For example, if a large truck runs into a small car, most people are confident that the car will get damaged. It also makes sense to them that the car would be damaged.

At other times we know an answer is correct, (that is we are very confident in our answer) but it doesn't really make sense. For example, many people are confident that if a person throws a boomerang, it will circle around and come back. But it doesn't make sense to them that it should come back. What makes sense to them is that the boomerang should just go in a straight line.

Please circle a number below indicating how much sense the following statement makes to you.

A table exerts a force upward on a book resting on it.

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

Please also rate this next statement for how much sense it makes to you.

A table does not exert a force upward on a book resting on it.

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

Part II - Instructions

The following is an explanation about the book on the table situation. As you read the explanation, you will be asked along the way about how understandable it is. At the end you will be asked how understandable the explanation is as a whole.

So we may keep track of your thoughts while you are reading, you will be asked to quickly answer the question about the book on the table again after each paragraph. Please answer this honestly each time.

(Note: Please move on to the next page only when finished with the current page. Also, please do not change answers or add or erase anything on previous pages while going through the explanation.)

Experimental Explanation

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Consider pushing down on a spring with your hand.

How much sense does it make to you that the spring would push up on your hand?

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

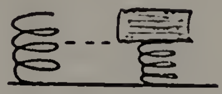
Is this situation different from the book on the table situation concerning whether or not there is an upward force? Please explain.

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

Now consider the case of a heavy dictionary being placed on a bedspring so the spring compresses some.



How much sense does it make to you that the bedspring pushes up on the book?

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

When the book is placed on the spring, the spring compresses. The further down the spring is pushed, the more it pushes back. The spring is compressed by the book to the point where it pushes back with a force equal to the book's weight. For example, if the book weighs 10 pounds, the spring compresses until it exerts an equal upward force of 10 pounds. In a similar way, if you hold a 30 pound dictionary in your outstretched hand, you have to exert an upward force of 30 pounds to hold it there.

How much sense does it make to you that the spring would exert a force of 10 pounds up on a book weighing 10 pounds?

1	2	3	4	5
Makes <u>no</u> sense to me	Makes <u>only a little</u> sense to me	Makes <u>some</u> sense to me	Makes <u>quite a bit</u> of sense to me	Makes <u>perfect</u> sense to me

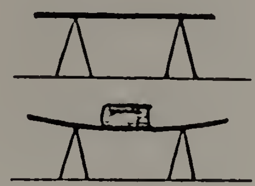
Is this situation different from the book on the table situation? Please explain.

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does <u>not</u> exert a force upward on a book resting on it.

Many people say the book on the spring is different than the book on the table. They say that although neither is alive, the spring compresses but the table is rigid. But is the table rigid? Imagine a flexible board between two sawhorses. If you were to push down on this board it would bend and push back, just like pushing down on the spring. The board would also push back on a book, just like the spring. Now imagine thicker and thicker boards.



How much sense does it make to you that the flexible board pushes up on the book?

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

What would happen if the board got thicker and thicker?

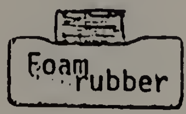
Is the book on the board situation different from the book on the table situation concerning whether or not there is an upward force? Please explain.

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

If you had a thick enough board, it would be just like a table. Both the board and the table would bend a tiny, tiny bit under the weight of a book. Another way to think of the table is like very stiff foam rubber. Even though the stiff foam rubber would not compress much under the weight of a book, it would compress some.



How much sense does it make to you that the foam rubber pushes up on the book?

1	2	3	4	5
Makes <u>no</u> sense to me	Makes <u>only a little</u> sense to me	Makes <u>some</u> sense to me	Makes <u>quite a bit</u> of sense to me	Makes <u>perfect</u> sense to me

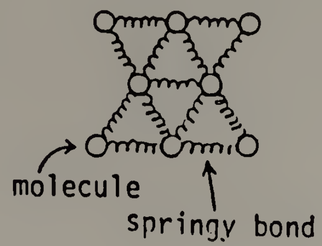
Is the book on the stiff foam rubber situation different from the book on the table situation concerning whether or not there is an upward force? Please explain.

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

[The table is composed of molecules which are connected to other molecules by bonds which are "springy." Thus the table has some amount of give or "bendiness" or "squishiness" to it.] If you were to look closely with a microscope you would see that the book causes a slight depression in the table. The table, just like the spring, the flexible board, or foam rubber, is bent or compressed some and thus pushes back. Like the spring holding the dictionary, the table bends or compresses just enough to provide an upward force equal to the book's weight.



Is the table deformable or springy at all? Please explain your thoughts.

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does <u>not</u> exert a force upward on a book resting on it.

To summarize, many people do not think the table can exert a force since it is rigid and lifeless. However they feel a spring can exert a force if a force is exerted on it because it "wants to get back to its original shape." Thus there seems to be a distinction between rigid objects and springy objects. However, if you look closely enough at a table it is springy [because of its molecular makeup]. Because of this springy nature of all matter, the table can and does exert a force upward on the book. Just like a spring, the table compresses (on a microscopic scale) until it is compressed enough to provide an upward force equal to the book's weight.

Following are two questions about the entire explanation on the preceding pages.

Is the explanation understandable and believable to you?

1	2	3	4	5
Not at all	Slightly	Moderately	Very	Completely

Does the explanation help the idea of an upward force from the table make sense?

1	2	3	4	5
Not at all	Slightly	Moderately	A good amount	A great deal

Control Explanation

In this exercise we will consider the question of whether a table pushes up on a book resting on it. Newton's third law says that the table does exert a force on the book. Newton's third law states: To every action there is always opposed an equal reaction: or, mutual actions of two bodies upon each other are always equal and directed to contrary parts. This is a word-for-word translation from the Principia. In modern usage, however, we would use force where Newton used the Latin word for action. So we could rewrite this passage as follows: If one object exerts a force on another, then the second also exerts a force on the first; these forces are equal in magnitude and opposite in direction.

Can you state Newton's third law in your own words?

Is the statement "for every force there is an equal and opposite force" understandable and believable to you?

1	2	3	4	5
Not at all	Slightly	Moderately	Very	Completely

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

Apply this idea to an athlete running. You now see that her act of pushing with her feet back against the ground (call it the action) also involves a push of the ground forward on her (call it the reaction). It is this reaction that propels her forward.

How much sense does it make to you that the ground pushes forward on the athlete?

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

In this and all other cases, it really makes no difference which force you call the action and which the reaction, because they occur at exactly the same time. The action does not "cause" the reaction. If the earth could not "push back" on her feet, the athlete could not push on the earth in the first place. Instead, she would slide around as on slippery ice. Action and reaction coexist. You cannot have one without the other. Most important, the two forces are not acting on the same body. In a way, they are like debt and credit. One is impossible without the other; they are equally large but of opposite sign, and they happen to two different objects.

Can you say in your own words what this paragraph is trying to argue?

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does <u>not</u> exert a force upward on a book resting on it.

Newton wrote: "Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone." This statement suggests that forces always arise as a result of mutual actions ("interactions") between objects. If object A pushes or pulls on B, then at the same time object B pushes or pulls with precisely equal force on A. These paired pulls and pushes are always equal in magnitude, opposite in direction, and on two different objects.

Can you say in your own words what this paragraph is trying to argue?

Does it make sense to you that the stone would push back on the finger?

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

Every day you see hundreds of examples of this law at work. A boat is propelled by the water that pushes forward on the oar while the oar pushes back on the water. A car is set in motion by the push of the ground on the tires as they push back on the ground; when friction is not sufficient, the push on the tires cannot start the car forward.

Can you say in your own words what this paragraph is trying to argue?

For each of these examples of the third law, could you rate how much sense it makes to you? (Place the number of your rating next to each example).

1	2	3	4	5
Makes <u>no</u> sense to me	Makes <u>only a little</u> sense to me	Makes <u>some</u> sense to me	Makes <u>quite a bit</u> of sense to me	Makes <u>perfect</u> sense to me

___Rowboat

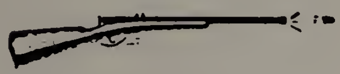
___Car

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does <u>not</u> exert a force upward on a book resting on it.

While accelerating a bullet forward, a rifle experiences recoil, or "kick." A balloon shoots forward while the air spurts out from it in the opposite direction. Many such effects are not easily observed. For example, when an apple falls, pulled down by its attraction to the earth, i.e., by its weight, the earth, in turn, accelerates upward slightly, pulled up by the attraction of the earth to the apple.



Can you say in your own words what this paragraph is trying to argue?

For each of these examples of the third law, could you rate how much sense it makes to you? (Place the number of your rating next to each example).

1	2	3	4	5
Makes no sense to me	Makes only a little sense to me	Makes some sense to me	Makes quite a bit of sense to me	Makes perfect sense to me

___Rifle

___Balloon

___Apple

How much do the examples in the last two paragraphs make the statement "For every force there is an equal and opposite force" understandable and believable?

1	2	3	4	5
Not at all	Slightly	Moderately	Very	Completely

What are you currently thinking?

___A table exerts a force upward on a book resting on it.

___A table does not exert a force upward on a book resting on it.

To summarize, many people say the table is not exerting a force upward on the book. However, the book is exerting a force downward on the table because of its weight. Therefore, because of Newton's third law, the table is exerting an equal force upward on the book.

Following are two questions about the entire explanation on the preceding pages.

Is the explanation understandable and believable to you?

1	2	3	4	5
Not at all	Slightly	Moderately	Very	Completely

Does the explanation help the idea of an upward force from the table make sense?

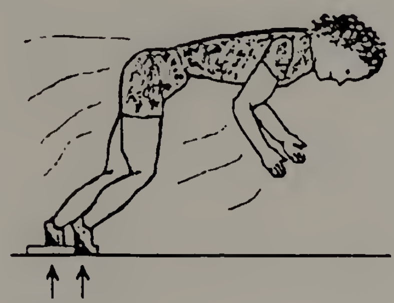
1	2	3	4	5
Not at all	Slightly	Moderately	A good amount	A great deal

Post-Questions

After the students had interacted with one of the three explanations, they then answered five post-questions. Two of these (the Table Problem and the Goat Problem) were identical to the pre-questions. All of the questions except the runner problem, reproduced below without confidence scales, were identical to the problems in the interviewing study (see appendix A).

RUNNER PROBLEM

To help get a good start in a race, a runner fixes some racing blocks firmly in the ground.



While the runner is taking off but is still in contact with the blocks:

___1) The blocks exert a force on the runner

___2) The blocks do not exert a force on the runner

If you said the blocks exert a force:

___A) The blocks and the runner each exert a force on the other, but the runner exerts a larger force.

___B) Each exerts a force, but the blocks exert a larger force.

___C) Each exerts a force, and the forces are the same size.

___D) Only the blocks exert a force.

If you said the blocks do not exert a force:

___E) The runner exerts a force on the blocks.

___F) The runner does not exert a force on the blocks.

APPENDIX E

DEFINITIONS OF TERMS

Agency. The power or ability to effect a change. In my consideration of physical systems, I am the prototypical center of agency, and my conception of the agency of each part of the system depends on my conception of my own ability to cause a change, and my conception of whether the part of the system under consideration could be a center of a particular type of agency. For example, according to Piaget (1969), young children view everything that moves as alive. They themselves are alive, and thus have power to move, and so they attribute the agency of life (including intentionality) to other objects which move, such as clouds and the sun. As an example of psychological agency, I might attribute anger to a dog which bit me but not to a stone which fell on my foot.

Analogical transitivity chain. A chain of connected thought situations from an anchor, through intermediate situations, to a target situation. Since the anchor is viewed as analogous to the closest situation, which is viewed as analogous to the next closest situation...which is viewed as analogous to the target, the anchor is viewed as analogous to the target. Although this type of chain does not have the rigor of a mathematical transitivity chain (e.g. A = B, B = C...Y = Z, therefore A = Z), it is often intuitively compelling.

Analogy. A conceptual system (the base) which is used in a comparison to another conceptual system (the target). The base is generally considered more simple or familiar, differing from the target in at least one feature normally assumed fixed, and the comparison is made so that relations in the base may be transferred to the target, thus eliminating the necessity of finding these relationships in the target by more direct means. An analogy is at the same level of abstraction as the target.

Analogy relation. The correspondence between the base and the target. (The term "analogy" is often loosely used to mean an analogy relation.)

Anchor. A situation is an anchor to someone if, in considering a question about the situation, what they intuitively believe agrees with scientific theory.

Base. See Analogy.

Bridge. A thought situation is considered a bridge if it is conceptually intermediate between two other situations.

Causal explanation. An explanation which illuminates an agent or set of agents which would lead to an observed or predicted result. In a causal explanation, agency of some sort is attributed to (or assumed to exist in) various parts of the system, and this agency is responsible for the observed or predicted results.

Causal model. An imageable model (i.e. using visual, kinesthetic, and/or auditory imagery) which involves considering entities (both oneself and other objects) as centers of action effecting or able to effect changes in other parts of the system under consideration.

<u>Causal reasoning</u>. Thinking using causal models.

<u>Conscious conceptual change</u>. The concepts in conscious working memory change or adjust to accommodate a new perspective - a new cognitive equilibrium is reached which results in a different perspective on the domain under conscious consideration. The change may not be permanent in the sense of being forever immediately accessible (it is a common experience to think "I know I understood that last week, but it escapes me now") but it is nevertheless a type of conceptual change. Long term conceptual change resulting in a new and permanent robust understanding is of course the goal of any attempt to teach to overcome misconceptions, but conscious conceptual change is undoubtedly an important part of long term conceptual change, and it has the important advantage that it may be studied in more depth.

<u>Direct causal reasoning</u>. Reasoning about a situation in which a source of agency is explicitly considered. For example, the table exerts an upward force on a book resting on it because it has the agency of springiness.

<u>Example (concrete)</u>. A thought situation which is an instance of a more abstract principle or concept.

<u>Formal explanation</u>. An explanation which argues that since a situation is an instance to which a certain principle applies, certain conclusions follow. Some examples: 1) Since an object is accelerating, by Newton's second law there must be a net force on it. 2) Since object A is exerting a force on object B, by Newton's third law, object B must therefore be exerting a force on object A. 3) Since the object has

gained energy, by the conservation of energy there must be a loss of energy elsewhere in the system.

Indirect causal reasoning. Reasoning about a situation in which a source of agency is assumed to exist from the observed effects. For example, the table is assumed to have agency enabling it to exert an upward force on a book resting on it because it must balance the downward force on the book due to gravity. If this upward force did not exist, the book would fall to the ground.

Inductive reasoning. By consideration of a number of examples, abstracting a concept or principle. Or, if the principle is already given, considering examples which support and illuminate the principle.

Mechanical causality. Causal reasoning about physical systems in a Newtonian framework. In particular, mechanical causality involves reasoning about force as involving an interaction of two bodies as opposed to force as an innate or acquired property of a single body (see naive causal reasoning).

Metaphor. A metaphor is a system which is considered as being another system. Thus metaphor involves more than a simple comparison of two conceptual systems (an analogy) in that the systems are seen to be essentially equivalent rather than simply functionally or structurally similar. A metaphor involves some ontological commitment, thus the wording "system A is system B," rather than simply "system A is like system B."

Model. A mental model consists of static or dynamic mental imagery (visual, kinesthetic, and/or auditory) which is considered as

representing, with some ontological status, the system under consideration. The difference between a model and a metaphor is a matter of degree rather than kind in that a model is more systematic than a metaphor.

Naive causal reasoning. This is reasoning in which agency which is not present under current scientific theory is attributed to objects. Thus, for example, clouds move because they are alive, or a moving billiard ball "has" force which keeps it going. Naive causal reasoning should not be termed "wrong" (it enables us to survive in a complex physical environment), but left alone it can sabotage deeper understanding of physics principles which rest on an understanding of mechanical causality.

Target. See Analogy.

Teleological explanation. An explanation which illuminates the goal or purpose toward which a system tends, thus explaining changes and strivings toward change in the system.

Thought experiment. A thought situation to which causal reasoning is applied for the purpose of explanation or prediction.

Thought situation. A concrete situation (vs. an abstraction such as an equation) which is considered without the benefit of any material referents. Examples of thought situations are analogies, thought experiments, and concrete examples.

Underground or implicit model. A model which is not consciously employed but which structures thinking about a system (e.g. the motion metaphor in calculus - the limit of a function as x approaches zero).

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