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ThinkerTools: Enabling Children to Understand Physical Laws

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Abstract

This project[1] is developing an approach to science education that enables sixth graders to learn principles underlying Newtonian mechanics, and to apply them in unfamiliar problem solving contexts. The students' learning is centered around problem solving and experimentation within a set of computer microworlds (i.e., interactive simulations). The objective is for students to gradually acquire an increasingly sophisticated causal model for reasoning about how forces affect the motion of objects. To facilitate the evolution of such a mental model, the microworlds incorporate a variety of linked alternative representations for force and motion, and a set of game-like problem solving activities designed to focus the students' inductive learning processes. As part of the pedagogical approach, students formalize what they learn into a set of laws, and critically examine these laws, using criteria such as correctness, generality, and parsimony. They then go on to apply their laws to a variety of real world problems. The idea is to synthesize the learning of the subject matter with learning about the nature of scientific knowledge -- its form, its evolution, and its application. Instructional trials found that the curriculum is equally effective for males and females, and for students of different ability levels. Further, sixth graders taught with this approach do better on classic force and motion problems than high school students taught using traditional methods.

1 Introduction

Research has demonstrated that students can succeed in high school and even college physics courses, while still maintaining many of their misconceptions and without acquiring an understanding the physical principles addressed in the course (Caramazza et al. (1981), Clement (1982), diSessa (1982), Larkin et al. (1980), McDermott (1984), Trowbridge & McDermott (1981), Viennot (1979), White (1983), and many others). For example, they make incorrect predictions about what will happen to the motion of a ball when it emerges from passing through a spiral tube (McClosky et al., (1980)). Such questions do not call for computation or the algebraic manipulation of formulas; rather, they require understanding the implications of the fundamental

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tenets of Newtonian mechanics. Students' failure to correctly answer such questions reveals a deficiency in their knowledge of the causal principles that underly the formulas they have been taught.

We believe that students need, at an early age, experiences that will enable them to acquire accurate causal models (Bobrow (Ed.) (1985), Gentner & Stevens (Eds.) (1983), White & Frederiksen (1986(a)) & (1986(b))) for how forces affect the motions of objects. This will inhibit the development of misconceptions and foster the type of understanding that older students appear to lack. In contrast to our view, many cognitive and educational theorists believe that attempts to teach children physics will inevitably fail (see, for example, Shafer & Adey (1981)). They argue that understanding physical principles requires formal operational thinking (Piaget & Garcia, 1964), and that many students have not reached this stage of cognitive development at the high school or even the college level, let alone at the elementary school level. Consequently, such students cannot be expected to master physical principles. We have found this not to be the case. This paper will describe an instructional approach that enabled sixth graders to understand important aspects of Newtonian mechanics. Further, it will illustrate how they also began to learn about the nature of science -- what are scientific laws, how do they evolve, and why are they useful?

2 The Progression of Microworlds & Subject Matter

The objective was for students to evolve a mental model of sufficient sophistication to enable them to analyze projectile motion problems (i.e., problems involving motion under a constant, uniform gravitational force). The desired model would incorporate such fundamental concepts of Newtonian mechanics as force, velocity, and acceleration, as well as causal principles, such as *forces cause changes in velocity*. In order to enable the students to acquire such a causal model, we created a progression of increasingly complex microworlds. Associated with each microworld is a set of problem solving activities and experiments designed to help the students discover the laws governing the microworld. These microworlds gradually introduce the full set of principles needed to analyze projectile motion problems. All of them require students to control the motion of a computer-generated graphic object via the application of forces. Within these simulations, the complications introduced by friction and gravity can be selectively eliminated, allowing students to encounter first simpler situations obeying Newton's first law (objects do not change their velocity unless a force is applied to them), and later to analyze more complex situations in terms of such basic laws. In addition, the microworlds incorporate a number of different representations for the application of forces and for the motions of objects. For example, there is the datacross (see Figure 1), which is essentially a pair of crossed "thermometers" that register the horizontal and vertical velocity components of an object via the amount of "mercury" in them. Also, there are wakes (also shown in Figure 1) that provide a record of an object's past speed and direction

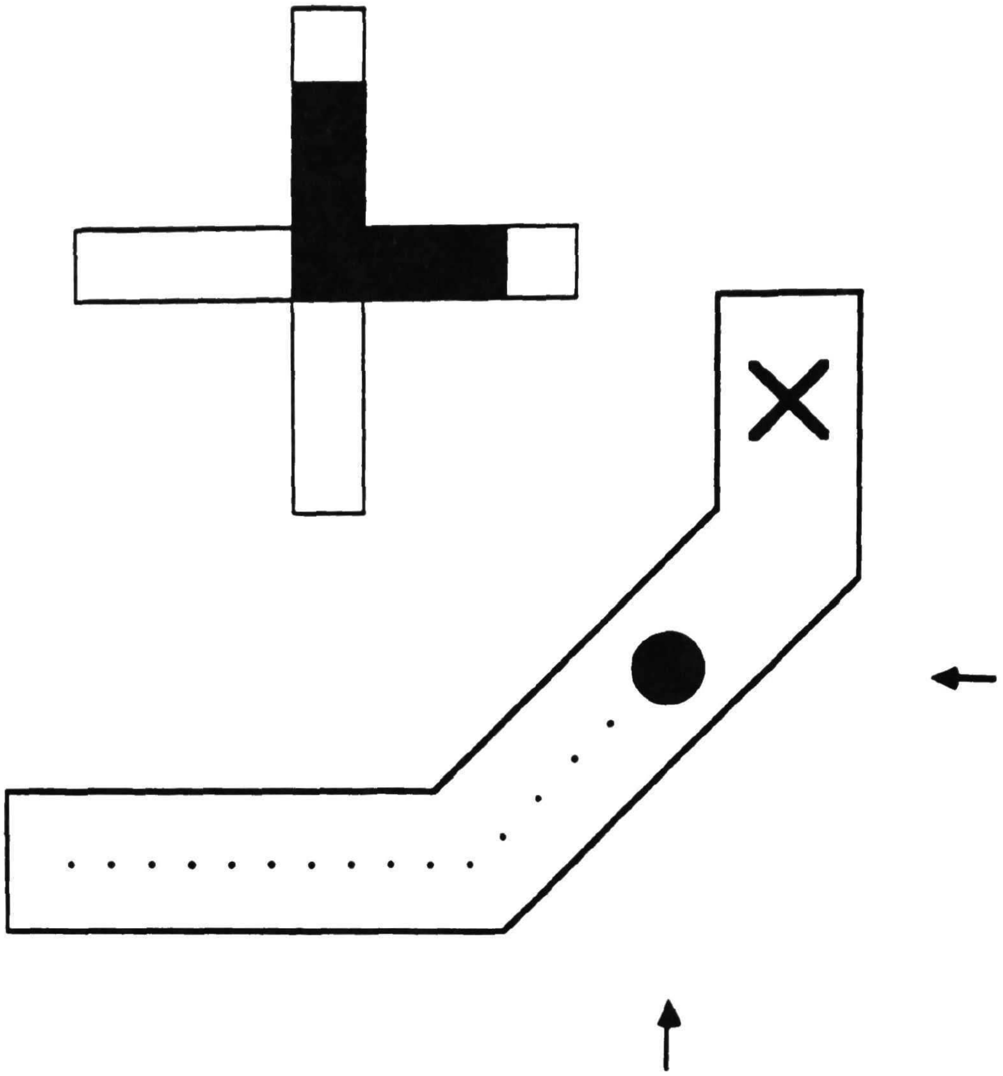

Figure 1: The Representation of Motion within the Microworlds

In this game, one must control the motion of the dot so that it navigates the track and stops on the target X. The shaded circle in the middle of the angled path is the dot. It represents a physical object which may be given fixed sized impulses in the left-right or up-down directions. In this figure the dot has been given the (optional) property of leaving "wakes" in the form of little dots laid down at regular time intervals. These denote, by their position and relative separation, the past history of the motion. The large cross in the middle of the figure is the "datacross" -- a device for displaying the instantaneous values of the X and Y velocity components. Here the datacross is depicting a velocity inclined at +45 degrees to the horizontal. The arrows at the bottom and right side of the figure continually point to the dot, unless it leaves the screen, in which case they "get stuck" at the edge of the screen. They represent the X and Y coordinates of the dot's position, and are useful for determining its location to within a quadrant when it is off the screen. Their motions, while the dot is on the screen, dynamically illustrate the X and Y components of the dot's velocity.

of motion by leaving a mark on the screen at fixed time intervals. These representations allow the effects of forces on an object's motion and velocity components to be directly observed, and thereby facilitate students' attempts to formulate the principles governing these causes and effects.

Microworld #1: At the beginning of the curriculum, we introduce a simple one-dimensional microworld which has no friction or gravity. In this world, students try to control the motion of an object (referred to as the "dot") by applying fixed sized impulses to the right (-->) or to the left (<--). The students observe that whenever they apply an impulse to the dot, it causes a change in its speed: If the impulse is applied in the same direction that the dot is moving, it adds to its speed; applied in the opposite direction, it subtracts from the speed. In this way, the students discover that a formalism they learned in second grade, scalar arithmetic (e.g., $3 - 2 = 1$), will enable them to make predictions about the effect that a particular impulse, or sequence of impulses, will have on the motion of the dot. As part of this process, the students have discovered a corollary of Newton's first law -- Whenever you apply an impulse to an object, you change its velocity.

Microworld #2: Next, the students are given a two-dimensional microworld. Again, there is no friction or gravity. In this world, the students can apply impulses up or down, as well as to the left or right. Through carefully designed problem solving activities (for example, see White, 1984), the students discover that the law they developed for the horizontal dimension applies equally well to the vertical dimension of the dot's velocity. Further, they learn that these two components of the dot's motion are independent of one another -- for instance, if you apply an upwards or downwards impulse, it has no effect on the horizontal velocity of the dot[2]. Finally, they acquire the foundation for an understanding of vector addition -- they learn how the vertical and horizontal velocity components combine to determine the speed and direction of the dot's motion.

Microworld #3: The next step is to provide students with a microworld where the rate at which they can apply impulses can be varied. The purpose of this microworld is to introduce students to continuous forces via a limit process: The students can repeatedly double the frequency with which they can apply impulses, while at the same time, the size of each impulse is halved. At the end of this process, the students are applying very small impulses closely spaced in time. In this way, the students learn to think of continuous forces, like gravity, as a lot of small impulses applied one after another. This enables students to apply their causal model, learned in the simpler

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[2] This is learned by giving one student the capability to apply only horizontal impulses to the dot and another the capability to apply only vertical impulses. The first student is then given a task that requires controlling the arrow whose motion represents the dot's horizontal velocity, and the second student has to control the arrow whose motion represents its vertical velocity. They discover that the other student's impulses have no effect on the motion of their arrow.

microworlds, to understand the effects of continuous forces. For example, they are asked to think about what happens when you throw a ball up into the air. They discover that gravity is constantly applying an impulse that continually adds a small amount to the vertical velocity of the ball in the downwards direction. This causes the ball to go upwards at a slower and slower rate until it finally stops, turns around, and accelerates downwards. By analyzing such problems, the students develop an understanding of acceleration and of **F=ma** for the case where the mass and the force are constant. In other words, they learn a simpler causal form of **F=ma**, that is, **F --> a**.

Microworld **#4**: Finally, the students are presented with a microworld in which gravity is acting, and they can again apply impulses to the left and right, as well as up and down. In this world, in the absence of other forces, motion is characterized by constant acceleration in the vertical dimension and constant speed in the horizontal dimension. The students are given problems of the form: "Imagine that you give two balls a horizontal push off the side of a table. One ball gets a soft push and the other ball gets a hard push. Both balls are pushed at the same time. Which ball hits the floor first?" Working in this microworld thus enables students to make connections to some interesting real world situations. Solving such problems requires the students to apply the causal model that they learned from interacting with the prior microworlds.

3 The Instructional Approach

The set of microworlds we have created focuses on, simplifies, and makes concrete certain aspects of Newtonian mechanics. The challenge was to devise instructional techniques, centered around the microworlds, that would facilitate students' acquisition of the desired mental model. A central aspect of the approach that we developed is to synthesize the teaching of subject matter with teaching about the form, evolution, and application of scientific knowledge. Students are given a variety of laws that have been proposed for a given microworld, and are asked to determine which laws are correct and which laws are incorrect (i.e., demonstrably false). Then, for the correct laws, they have to devise criteria for deciding which laws are better than others. Finally, they have to apply their laws to real world contexts and thereby discover that the laws are general and enable one to make predictions about a wide range of physical phenomena.

Within each of the existing four modules of the curriculum (corresponding to the four microworlds described above), instruction was divided into four distinct phases:

The Motivation Phase. In the first phase, students are asked to make predictions about what they think will happen in simple real world contexts. For example, in the first module of the curriculum, the teacher asks the students: "Imagine that we have a ball resting on a frictionless surface and we blow on the ball. Then, as the ball is moving along, we give it a blow, the same size as the first, in the opposite direction. What will be the effect of this second blow on the motion of the ball?" The teacher simply tabulates the different answers and reasons for these answers without commenting on their correctness. This process demonstrates to the students that not everyone holds the same beliefs. For instance, some think that the second blow will cause the ball to turn around and go in the opposite direction, others think that it will make the ball stop, and yet others believe that it will simply cause the ball to slow down. Since not everyone can be right, students are motivated to find out who has correct explanations and who has misconceptions. Further, since the predictions are about the behaviors of real world objects, this phase sets up a potential link between what happens in the computer microworld and the real world.

The Evolution Phase. In this phase students solve problems and perform experiments in the context of the computer microworld. For instance, one of the problems in the first module requires the students to make the dot hit a stationary target while moving at a specified speed. Once the student succeeds, the dot returns to its starting location and a new target speed is specified. By attempting to solve this problem, the students learn how impulses affect the speed of the dot. As described in the previous section, the computer microworld increases in complexity with each new module of the curriculum. The problems and experiments are designed and sequenced to build upon the students' prior knowledge and to enable them to induce increasingly sophisticated concepts and laws relevant to understanding the implications of Newton's laws of motion.

The Formalization Phase. In this phase the students are asked to evaluate a set of laws formulated to describe the behavior of objects within the microworld. Examples of such laws are (1) *whenever you give the dot an impulse to the left, it slows down*, and (2) *if the dot is moving, and you do not apply an impulse, it will keep moving at the same speed*. Initially students are asked to sort the laws into two piles -- those that they can prove wrong and those for which they cannot find a counterexample. Then, for the subset of "true" laws, they are asked to pick the rule they like best: "if you could only have one of these rules in your head to base predictions on, which one would you pick and why?" This activity typically engenders discussions of (1) the precision of a rule's predictions, (2) the range of situations to which it applies, and (3) its simplicity and memorability.

The Transfer Phase. In this phase the objective is to get students to appreciate how the rule they have selected applies to real world contexts. In the first stage of this process, students apply their rule to the predictive question that they were asked at the beginning of the instructional cycle. They then compare the answer that the rule generates to the set of answers generated by the class. For answers that differ, students go to the microworld and experiment, for example, by putting friction and/or gravity into the microworld, to see which of their "wrong" predictions can become correct predictions under these more complex circumstances. In the second stage of the transfer process, students conduct experiments with real world objects, or design their own experiments to illustrate how the rule they evolved in the microworld context holds in these real world contexts.

4 Experimental Results

The curriculum was implemented by a teacher who taught five science classes in the sixth grade of a middle school located in a middle class Boston suburb. One of the five classes was used for a pilot trial of the first two modules of the curriculum. Of the remaining classes, two were used as a peer control group (containing 37 students), and the other two were given the ThinkerTools curriculum (containing 41 students). The curriculum took two months to complete. During this period, the students had a science class every school day for 45 minutes. The ThinkerTools curriculum occupied the entire class period. Students in the control classes received the standard curriculum which, at this point in the year, was devoted to a unit on inventions. All students had completed a physics unit earlier in the year which included material on Newton's laws.

In addition to the control group of sixth grade students, a second control group was employed, consisting of two classes of high school physics students (containing 41 students) drawn from the same school system as the sixth graders. These students had just completed two and one half months studying Newtonian mechanics using the text book "Concepts in Physics" (Miller, Dillon, & Smith (1980)).

We utilized a variety of evaluation instruments to help us determine the effectiveness of the ThinkerTools curriculum. During the course we observed numerous classroom sessions and kept videotape and audiotape records of certain sessions. At the end of the course we administered three written tests measuring: (1) ability to translate between the alternative representations of motion (datacrosses and wakes -- see Figure 1) employed within the curriculum, (2) subject matter knowledge in the computer microworld context, and (3) transfer of the underlying principles to real-world contexts. This third test was also given to the two control groups. In addition, following the administration of the written tests, seven of the ThinkerTools students were interviewed on an individual basis. These protocols allowed us to explore in depth the nature of the mental models they had acquired.

Since the first two tests were given only to the experimental subjects, we will focus in this limited space on the results of the third test. The findings will be discussed with respect to the two primary objectives of the course: (1) understanding the principles underlying Newtonian mechanics, and (2) learning about the form and evolution of scientific knowledge.

4.1 Understanding Newtonian Mechanics

The experimental students did well on the first two tests, with a third of them getting more than ninety percent of the questions correct. Protocols of high scoring students reveal that their pattern of correct answers was produced by the consistent application of the desired mental model for reasoning about force and motion problems. This is in marked contrast to the inconsistent and misconception fraught reasoning that sixth graders display prior to instruction (White & Horwitz, in preparation), and that high school physics students exhibit following a traditional physics course (White, 1983).

The third test, administered to the experimental group and two control groups, measures students' understanding of Newtonian mechanics in real world problem solving contexts. It is composed of questions used by other researchers in studying misconceptions among physics students (Clement, diSessa, McClosky, McDermott, Minstrell, White). The particular questions used are simple predictive questions to which high school and college students frequently give wrong answers. They all require reasoning from basic principles, rather than constraint-based, algebraic problem solving.

In the first analysis of this transfer test, we compared sixth graders who had the ThinkerTools curriculum with those who did not. A three way between subjects analysis of variance was carried out with (1) treatment (experimental versus control), (2) gender, and (3) ability (low, middle, and high, based upon California Achievement Test (CAT) total scores) as the three factors. With this design we could assess the effectiveness of the experimental curriculum for subjects of each gender and ability level. There was a highly significant main effect of instructional treatment ($F_{1,62}=62.9$, $p<.0001$). The average number of questions correct for the experimental subjects was 11.15 out of 17, while the average for the control subjects was 7.56. In addition, there was no significant interaction of gender with treatment ($F_{1,62}=.219$, $p=.64$), or ability with treatment ($F_{2,62}=.834$, $p=.44$). Thus, the ThinkerTools curriculum was equally effective for girls and boys as well as for students of different ability levels as measured by the CAT.

With respect to the ThinkerTools students, the questions on the test can be classified into two categories:

1. Those that involve the application of a principle taught in the course and that the students have applied in a context similar to the one presented in the problem; and
2. Those that involve a principle addressed in the course but that the students have never applied to the particular context presented in the problem.

An item analysis revealed that the experimental students did better than the control students on both types of problems. This suggests that the ThinkerTools students not only learned the principles focused on in the course, but also could apply them to unfamiliar contexts.

Finally, it is noteworthy that the Thinkertools students also did significantly better on this transfer test than the high school physics students ($t_{80} = 1.7$, $p < .05$), who were on the average six years older and had been taught about force and motion using traditional methods. An item analysis revealed interesting differences between these groups. The ThinkerTools students performed better (in some cases dramatically better) than the high school physics students on problems that involved analyzing the effects of forces in terms of velocity components. The high school students, however, performed better on problems that involved constraint forces (such as a fixed length string constraining the motion of a pendulum bob). This latter result is not too surprising, since constraint forces were not dealt with in the ThinkerTools curriculum.

4.2 Acquiring Scientific Inquiry Skills

In addition to teaching students principles underlying Newtonian mechanics, we had the symbiotic goal of helping them learn about the form, evolution, and application of scientific knowledge. In evaluating our success with respect to this second major objective of the curriculum, we relied partly upon observations of students' classroom performance. For instance, we examined the quality of the laws and experiments that they formulated for themselves, as well as the sophistication of the discussions they held when they were attempting to select the best law. In addition, we looked at the results of the written tests, particularly the transfer test, to aid in this aspect of the evaluation.

Understanding the Form of Scientific Knowledge. Knowing the characteristics of a useful scientific law is an important aspect of understanding the form of scientific knowledge. The instructional technique we developed was to present students with alternative laws for each microworld, and have them select the best law. We observed that when students were evaluating these sets of laws, they spontaneously engaged in discussions concerning the simplicity of a law, the precision of its predictions, and its range of applicability. The set of laws was carefully constructed to elicit such discussions and this approach thus appears to have been highly successful.

Developing Scientific Inquiry Skills. It is important to understand that falsification is part of the process by which scientific knowledge evolves. For a rule to be a potential scientific law, it must be capable of being proven wrong. Being able to develop and reason from counter evidence is an important scientific inquiry skill. We observed that when the students were evaluating the sets of laws given to them, they were adept at designing experiments that would falsify a particular law.

When we went on to look at what the students did when they formulated laws for themselves, there were clear limits to their scientific inquiry skills. For example, one group of students discovered the "linear friction law": in the microworld the effect of friction is linearly proportional to the speed with which the object is moving. The consequence is that when you apply a sequence of impulses to the dot, it does not matter whether you apply them one right after the other or whether you separate them further in time, the dot will come to rest at the same point. The students discovered this fact, but they did not fully explore its implications, nor did they go on to investigate whether it was true for the kind of real world friction that affects, for instance, rolling balls or sliding hockey pucks.

If one looks at our instructional approach, this limitation in their inquiry skills is understandable. We gave the students activities to help them induce the laws, as well as sets of possible laws to evaluate, and real world activities that enabled them to see that the laws generalized. Toward the end of the course they were asked to formulate their own laws and to design real world activities that illustrated the laws. This was clearly too abrupt a transition, and an important area of our future research will be the development of bridging activities that enable a more gradual transition to independent scientific discovery.

Acquiring Scientific Problem Solving Skills. Students need to understand that the laws they are evolving are of increasing general applicability, and need to be able to apply them in new contexts. Based upon classroom observations and the results of the transfer test, we see that the students were indeed able to generalize principles derived in the microworld contexts to a variety of simple real world contexts. This was achieved by a process of abstracting what they learned from the computer microworld into a set of laws and then learning how to map the laws onto different real world problem solving situations.

The general conclusion is that the ThinkerTools students learned that a useful scientific law is a concise principle that enables predictions across different contexts. In addition, they developed skill at designing experiments to falsify or show the limitations of a law, and applying a given law to a variety of different domains. This view of scientific knowledge and these inquiry skills are an important component of understanding what science is all about.

5 Discussion

The design of the curriculum was based upon extensive protocol studies of sixth graders' reasoning about force and motion problems. Based upon this research, we determined which aspects of their prior knowledge we could build upon, and which misconceptions we could use to motivate their learning about Newtonian mechanics. The progression of increasingly complex computer microworlds was then designed to correspond to the desired evolution of the students' understanding of the phenomena.

Further, the design of the microworld made abstractions, such as Cartesian components of displacement and velocity, into concrete observable data-objects, and introduced simplifications, such as quantized impulses, that enabled students to learn and make concrete what are normally regarded as abstract and difficult concepts.

Another aspect of the instructional approach that we believe was crucial to its success is the process of reification -- students were asked to consider alternative descriptions of what they learned from the computer microworld in the form of a set of laws, and had to evaluate the properties of the various laws. This enabled the students to develop a concept of what it was they were trying to learn -- for example, rather than learning a set of facts, they were trying to induce a set of laws and learn about the properties of scientific laws. Further, the process of getting students to apply the laws they induced from the microworld to real world contexts was important both for their understanding of Newtonian mechanics and for their perception of the nature of scientific knowledge. They learned that their laws apply in a wide range of contexts and they gained experience in transferring what they learned in one context (i.e., the computer microworld) to another context (i.e., a particular real world situation). We conjecture that these formalization and transfer phases of our curriculum are responsible for the ThinkerTools students being able to apply their knowledge to unfamiliar contexts -- a result which is rarely obtained in educational research.

6 References

Bobrow, D.G. (Ed.) (1985). Qualitative Reasoning about Physical Systems. Cambridge, MA: MIT Press.

Caramazza, A., McCloskey, M., & Green B. (1981). Naive beliefs in "sophisticated" subjects: Misconceptions about trajectories of objects. Cognition, 9, 117-123.

Clement, J. (1982). Students' preconceptions in elementary mechanics. American Journal of Physics, 50, 66-71.

diSessa, A. (1982). Unlearning Aristotelian physics: a study of knowledge-based learning, Cognitive Science, 6(1), 37-75.

Gentner, D., & Stevens, A. (Eds.) (1983). Mental Models. Hillsdale, NJ: Lawrence Erlbaum Associates.

Larkin, J.H., McDermott, J., Simon, D.P., & Simon, H.A. (1980). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. Science, 210, 1139-1141.

McDermott, L.C. (1984). Research on conceptual understanding in mechanics. Physics Today, 37, 24-32.

Piaget, J. & Garcia, R. (1964). Understanding causality. New York: Norton.

Shayer, M. & Adey, P. (1981). Towards a Science of Science Teaching. London, England: Heinemann Educational Books.

Trowbridge, D.E., & McDermott, L.C. (1981). Investigation of student understanding of the concept of acceleration in one dimension. American Journal of Physics, 49, 242-253.

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. European Journal of Science Education, 1, 205-221.

White, B. & Horwitz, P. (in preparation). Multiple Muddles: Novice Reasoning about Force and Motion.

White, B. & Frederiksen, J. (1986 (a)). Progressions of qualitative models as a foundation for intelligent learning environments. BBN Report No. 6277. Cambridge, MA. (To appear in Artificial Intelligence.)

White, B. & Frederiksen, J. (1986 (b)). Intelligent tutoring systems based upon qualitative model evolutions. In Proceedings of the Fifth National Conference on Artificial Intelligence. Philadelphia, PA.

White, B. (1984). Designing computer activities to help physics students understand Newton's laws of motion. In. Cognition and Instruction, 1, 69-108.

White, B. (1983). Sources of difficulty in understanding Newtonian dynamics. In Cognitive Science, 7(1), 41-65.