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ABSTRACT

During the past 15 years, physics education research has revealed many surprising things about the difficulties introductory physics students have in learning physics. At the same time, the ongoing revolution in information technology has led to new tools for creating innovative educational environments. In response to these two developments, a wide variety of new models of physics instruction are beginning to appear. This paper reviews some of the findings of physics education research, putting them into the context of a theory of thinking and learning. Some of the most promising instructional models currently being developed in the U.S. are discussed. (Contains 20 references and 12 figures.) (Author/WRM)

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ED 438 184

New Models of Physics Instruction Based on Physics Education Research

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Abstract

During the past fifteen years, physics education research has taught us many surprising things about the difficulties introductory university students have in learning physics. At the same time, the ongoing revolution in information technology has led to new tools for creating innovative educational environments. In response to these two developments, a wide variety of new models of physics instruction are beginning to appear. We review some of the findings of physics education research, putting them into the context of a theory of thinking and learning. Some of the most promising instructional models currently being developed in the US are discussed.

Introduction

Over the past few decades, changes have taken place that require a change in how we teach introductory university physics. First, a larger fraction of the population is graduating high school and going on to universities than in previous times. Many of these students are concerned about finding jobs in an increasingly technological workplace environment, and so are enrolling in technical curricula that require physics. As a result, a larger fraction of our students today appear inadequately prepared to take university physics than was the case in the past.

Second, for those of us in publicly supported institutions, the governments and the populace that employ us appear more likely to hold the educational system (and therefore its teachers and administrators) directly responsible for the students' learning -- or lack of it -- then they were in the past. In previous times, the individual student was often held personally responsible for their learning and less attention was paid to the effectiveness of teaching.

As a result, the task of the physics teacher today is to figure out how to help a much larger fraction of the population understand how the world works, how to think logically, and how to evaluate science. This is doubly important in democratic countries such as the USA and Germany in which a large fraction of the adult population is involved in selecting its leaders -- those leaders who will make decisions not only on the support of basic science, but on many items that depend intimately on technological information. Having a populace which cannot be fooled by the misuse of science and by scientific charlatanism would be of considerable value.

We may ask ourselves whether we are perhaps in the best of all possible worlds and are already achieving these goals. Does traditional physics teaching "work" in the introductory physics classroom? Unfortunately, detailed examinations by many physics education researchers have shown that it does not work well for a large fraction of our students. Many of our students fail to gain the skills that permit them go on to success in advanced science courses.

This can have strong negative consequences. When many students fail, faculties may be pressured to pass more students, with the result being a lowering of standards. This of course is ineffective in the long run. The lowering of standards simply postpones the time at which the unprepared

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student will be unable to meet the requirement either of more advanced courses or of a job in the technological workplace.

The nature of the difficulty, as illuminated by physics education research, appears to be a kind of "impedance mismatch". The professor sends out information and sees it reflected back in a similar or identical form (Fig. 1), but little information has actually gotten through to the other side.

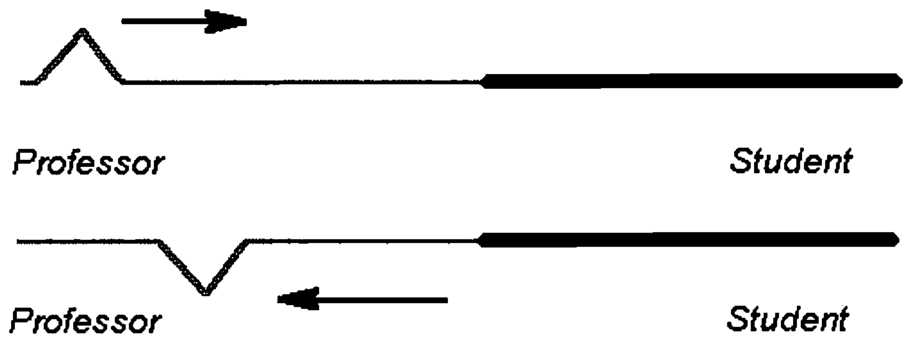

Fig. 1: The fact that something "comes back as we sent it out" does not mean that much has "gotten through to the student", especially if students possess a large inertia!

If we are to understand these difficulties we must treat the problem scientifically by observing carefully the phenomena we want to understand. From educators and cognitive psychologists we learn two important lessons.

- To understand what will work, we have to concentrate on what the student is learning instead of on what we are teaching.
- We have to do more than evaluate our students' success. We have to listen and analyze what they are thinking and how they learn.

A Model of Thinking and Learning

Over the past three decades, cognitive psychologists and educators have begun to build a model of learning that seems to provide a framework for this analysis. This framework is a relatively recent growth based on the ideas and experimental methods learned from psychologists Jean Piaget, Lev Vygotsky, and the gestalt school of psychology, among others. I refer to this as the *constructivist model of cognition* and extract four principles that help us understand the kinds of difficulties that take place in a physics class.[1]

1. Constructivism
2. Context
3. Change
4. Variability

Principle 1: The Constructivist Principle

Students "construct" their ideas and observations -- pulling together what they see and hear into a "mental model".

This construction is an active but in most cases, automatic and unconscious process. Think of language learning by a small child as a prototypical example. Children create their own grammars from what they hear. (The fact that they don't always create the same rules as their parents have is one of the facts that causes languages to evolve.) A nice example of the way the brain constructs is seen in Fig. 2. The picture will be immediately obvious to some, more difficult for others. (See the footnote if you have looked at the picture for a while and can't make out an animal.[2]) The image is in your mind, created by your brain pulling together the loosely related spots and "constructing" the image. Once you have seen it, it will be hard to remember what it looked like to you when you couldn't see it.

Fig. 2: A picture of an animal. "Some assembly required."

For more complex situations, the brain constructs a pattern or "mental model" of the situation in order to understand and analyze it. When I say "mental model", you should not construct a picture of something machine-like. That isn't the nature of the phenomenon. Some properties of mental models (MMs) can be summarized in the following statements:

- MMs consist of propositions, images, rules of procedure, and statements as to the context in which they are to be used.
- MMs may be incomplete and contain contradictory elements.
- Elements of MMs don't have firm boundaries. Similar elements may get confused.
- Elements of a MM may be *situated* -- that is, they may be associated with a particular environment or class of problem.

The last has a rather direct implication for a physics class. Students may well accept an idea within the bounds of a physics class or carefully constructed experiment, but not consider that it has any implications for real world events or for their personal experience. We elaborate this in our second principle.

Principle 2: The Context Principle
It is reasonably easy to learn something that matches or extends an existing mental model.

This has two corollaries.

- It's hard to learn something we don't almost already know.
- Everything we learn is learned via interpretation within a "context".

This is illustrated with another visual image in the picture at the right taken from a cleverly designed greeting card by artist Jay Palevsky.[3] When the two halves of the card are pulled apart, they reveal that they are part of a different picture than the one you originally perceived. The change of context changes the way our minds interpret the visual image.

Fig. 3a: What is this? Are you sure?

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Fig. 3b: The picture in Fig. 3a has been divided in half down the middle and occupies the left and right quarters of this figure.

(To see the opened card, turn to the next page and look carefully at Fig. 3b.)

The important point to realize is that the "context" in which a student interprets any information in a physics course includes not just the classroom or laboratory environment, but the context of all their previous learning and experience. The most important context is the state of the student's mind at the instant the information is presented.

Principle 3: The Change Principle
It is very difficult to change an established mental model substantially.

This is nicely illustrated by the famous picture shown in Figure 4. This ambiguous figure can be seen either as a young woman or an old woman.[4] The interesting part of the story of this figure is that it was used in a psychology experiment at Columbia University. Two unambiguous figures were prepared -- one of the old woman and one of the young woman. Half of the class were given one of the figures, half the other. Then the figures were collected and the entire class shown the ambiguous figure. In subsequent class discussion, those who had seen one of the figures had great difficulty in seeing the second possibility, even when it was described in detail by someone in the other half of the class.

Fig. 4: A drawing of an old woman. Or is it a young one?

Students often have a similar difficulty in a physics class. If they have already misinterpreted previously given knowledge or previous experience, it may be very difficult for them to put the correct interpretation on what a teacher says. The fact that this problem is widespread and occurs in many areas of an introductory physics class has been well documented in the physics education literature.

Two of the consistent observations of this research are:

- Reading and listening to lectures are, for most students, ineffective ways of changing their mental models.

This is even the case if students are "warned" about common misconceptions.

- One effective way of changing a mental model is "cognitive conflict".

This means that environments in which students are encouraged to elicit and confront the mental models they have are more effective in changing those models than environments in which the "correct" information is simply presented.

Principle 4: The "Distribution Function" Principle
Since individuals construct their own mental states based on their own experiences and personal makeup, different students have different learning styles and responses.

This is by now very well documented by a large number of psychological studies.[5] Some students respond better to visual information, others to symbology. Many students seem to learn better using "hands-on" activities as compared to listening to abstract reasoning. There are many variables, and a good knowledge of physics requires calling on a wide variety of different media and manners of coding and conveying information. Two corollaries result.

- There may not be a unique answer to the question: "What is the best way to teach a subject?"
- Our individual experiences may have little relevance to how to best teach our students (especially if we are physicists!).

Implications of the Cognitive Principles for Physics Teaching

I have taken my examples from the human visual response since they are dramatic, many people easily see the illusions, and they clearly illustrate the principles. However, the principles are general and have a powerful impact in the physics class as well. With the model in the back of our minds we must raise some concerns that are often neglected in a traditional physics class.

- We have to be concerned that our students not only "have" the material but that they "make sense of it" and can use it effectively.
- If we are going to make deep changes in the way our students think, we are going to have to help them confront their incorrect beliefs.
- We must find new ways to help students understand concepts that they do not naturally build.
- We must find ways to actively engage students who learn differently than we do.

Learning about the difficulties: Physics education research

If we are to really understand what is happening when we try to teach physics we have to study it as a scientific problem. Human beings have a strong tendency towards "wishful thinking" -- to seeing what it is they want to see. This does not imply that we are duplicitous, just prone to "hopeful misinterpretation". It is this tendency that the scientific method, as carried out by an active and skeptical research community, is specifically designed to combat.

If we are to find out what is really going on in our classes, we will have to do research. In the context of physics education, this means the direct observation and interpretation of student behavior, especially detailed interviews. Our standard examinations, designed as they are for evaluation of student success rather than for understanding student difficulties, do not usually suffice. A research evaluation may be carried out through observational (as opposed to instructional) interviews, and occasionally, by means of other carefully developed testing instruments.

One approach to the linking of research to the development of instructional materials is the cyclic process practiced by Lillian McDermott and her Physics Education Group at the University of Washington.[6] In this process, research on student understanding illuminates the difficulties in current instruction. The results of the research can be used to design new curricula and teaching approaches, which lead to modified instruction. This process cycles in a helix of continuous educational improvement.

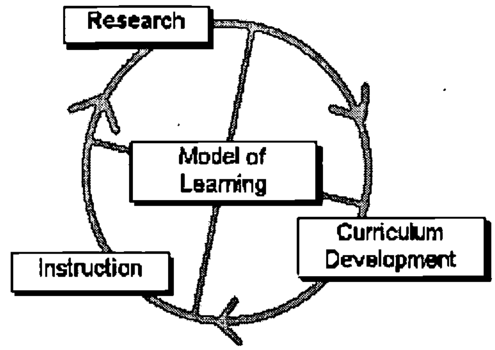

Fig. 5: "McDermott's Wheel" - illustrating the role of research in curriculum reform.

Of course, to understand what one sees in a research situation one must have a model or theory of the system under investigation in order to know what to look for and to make sense of what one sees. On the other side, the experimental observations may cause us to refine or modify our theoretical model. I represent this process schematically as "McDermott's Wheel" in Fig. 5, with the model of cognition and learning serving as the axle about which the wheel rotates.

Some Research-Based Active-Engagement Instructional Methods

Over the past few years, a number of curricula have been developed in the USA that are based on the constructivist model of student thinking and learning and which have evolved using the research/curriculum reform/instruction cycle. I refer to these as *active engagement classes*. They all have in common a focus on what it is the students actually do and on what the effect of that activity is. A few examples of active engagement classes are:

Full Studio Models

Physics by Inquiry (Lillian McDermott, et al., University of Washington)
Workshop Physics (Priscilla Laws, Dickinson College)
The Physics Studio (Jack Wilson, Rensselaer Polytechnic Institution)

Discovery Labs:

Tools for Scientific Thinking (R. Thornton, Tufts; D. Sokoloff, U. of Oregon)
RealTime Physics (R. Thornton, Tufts; D. Sokoloff, U. of Oregon and P. Laws, Dickinson College)

Lecture Based Models:

Active Learning Physics System (Alan van Heuvelen, Ohio State University)
Peer Instruction/ConcepTests (Eric Mazur, Harvard University)
Interactive Demos (R. Thornton, Tufts; D. Sokoloff, U. of Oregon)

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Recitation Based Models:

Cooperative Problem Solving (Ken and Pat Heller, University of Minnesota)
Tutorials in Introductory Physics (Lillian McDermott, et al., University of Washington)
Mathematical Tutorials (E. Redish et al., University of Maryland)

The traditional model of introductory university physics has a number of characteristics. As taught in the USA it has the following common features.

- It is content oriented.
- It has 3-4 hours of lecture and 1-0 hours of problem solving recitation per week.
- If there is a laboratory, it will be 2-3 hours and "cookbook" in nature; that is, students will go through a prescribed series of steps in order to demonstrate the truth of something taught in lecture or read in the book.
- The instructor is active during the class session while the students are passive during the class period (at least during lectures, and often during recitation).
- The instructor expects the student to undergo active learning activities outside of the class section, in reading, problem solving, etc.

The focus of the class is, in practice for most students, the lecture. The nature of this experience can be seen clearly in the structure of the classroom. A typical lecture room is illustrated schematically in Fig. 6.[7]

All students are turned to face the lecturer -- the focus of all attention. An active engagement class has somewhat different characteristics.

- The course is *student oriented.* What the students are actually doing in class is the focus of the course.
- Laboratories in this model are of the "discovery" type; that is, students are guided to observe phenomena and build for themselves the fundamental idea via observation.
- The course may include explicit training of reasoning.
- The student is expected to be intellectually active during the class.

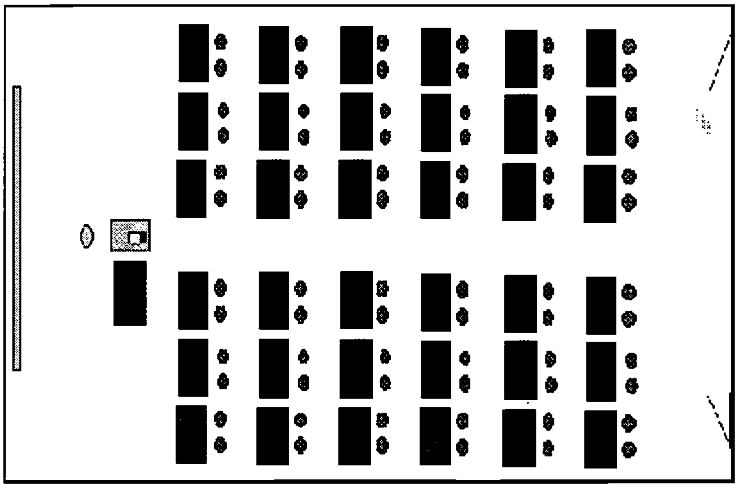

Fig. 6: The structure of a typical lecture classroom.

I have grouped the active engagement classes I will discuss into four groups. In the full studio classes, the entire class time is taken up by periods in which the students are actively engaged with exploring the physics using some laboratory equipment. Only a small fraction of the period may be spent with a teacher lecturing to the students. These classes tend to be more expensive, both in terms of faculty time, space, and equipment required than the traditional lecture format. Other models of instruction have therefore been developed that replace one or more of the elements of the traditional structure by an active engagement activity. Laboratory-based models replace the traditional laboratory by a discovery type laboratory. Recitation-based models replace the recitation in which an instructors models problem solving for an hour by a mini-lab in which the students carry out guided discovery experiments and learn reasoning in groups guided by worksheets. Lecture-based models retain the timing and the lecture hall, but modify the activities carried out by the students during lecture.

Full Studio Models

Physics by Inquiry

One of the earlier prototypes of the full studio courses was *Physics by Inquiry*,[8] developed by Lillian McDermott and her colleagues at the University of Washington over a period of nearly two decades. The course was developed for students studying to be teachers (*pre-service teachers* in the American terminology). The course is a full guided discovery laboratory. There is no lecture, only two laboratory periods of two hours each. During these periods, students work in pairs with simple equipment and are guided to reason through physical examples with simple apparatus and carefully prepared worksheets. A sample apparatus for the unit on light is shown in Fig. 7. The worksheets are based on research in student understanding and try to put the students in situations where their confusions will be elicited in their predictions of how a system will behave. When the system fails to behave as the student predicts, a cognitive conflict results. Trained facilitators (approximately one for every 10-15 students) help students to find their own path to understanding by guiding them with carefully chosen questions.

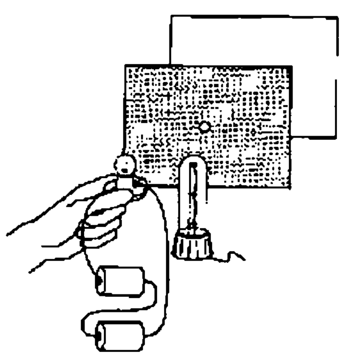

Fig. 7: A simple apparatus from *Physics by Inquiry*.

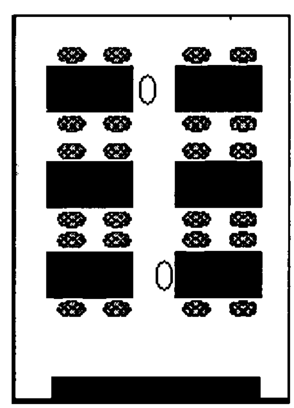

Fig. 8: The structure of a typical inquiry-based course classroom.

The structure of the classroom (see Fig. 8) illustrates the fundamental difference between this class and the traditional lecture. The focus of the students' attention is clearly the equipment and the interaction of the group, not the instructor.

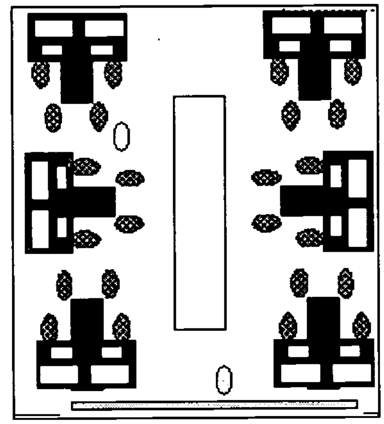
Fig. 9: A typical workshop or studio classroom layout.

Workshop Physics/Physics Studio

Among the groups that have developed inquiry style classes for the calculus-based university physics course, two stand out. Both the *Workshop Physics*[9] class developed at Dickinson College by Priscilla Laws, and *the Physics Studio*[10] developed at Rensselaer Polytechnic Institute by Jack Wilson, make strong use of computer equipment to give the student a more quantitative view of the world. What it is the students actually do in this class is hinted at by the structure of the classroom, shown in Fig. 9. The students function in groups as in the inquiry-style classroom, but each pair of students works with a computer connected to an analog to digital conversion device such as the Universal Lab Interface box (ULI).[11] A variety of probes can be connected to the box, including position or angle detectors, force probes, pressure and voltage sensors, etc. The computer stations also contain calculational and modeling tools such as a spreadsheet, programming language, and symbolic manipulator. These classes are also held in two hour periods in which most of the student time is spent with apparatus making observations and building mathematical models of their results. The classroom contains a central area for common demonstrations and many class periods may include brief lecture segments or whole-class discussions.

These classes use worksheets (in Workshop Physics) or on-screen lessons (in the Physics Studio) to help guide the student through the process of carrying out, making sense of, and modeling their experiments. In many cases, the experiments will be enabled by cleverly designed apparatus that, in conjunction with the ULI data acquisition probes, provides the student with a simple and direct quantitative view of what otherwise might be an obscure and confusing long chain of inferences. In Fig. 10 we show a "chaos machine" from Workshop Physics.[12]

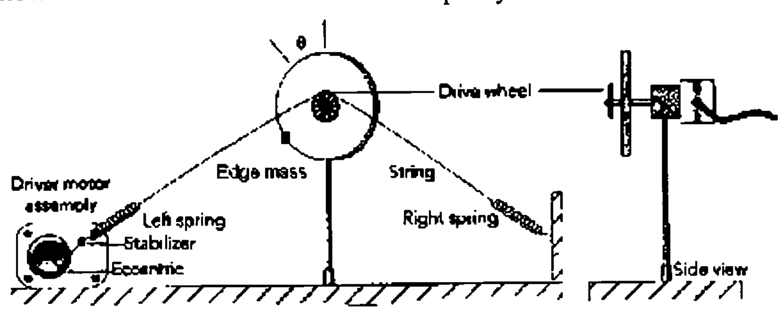

Fig. 10: A "chaos machine"

The device is a van der Pol oscillator -- a wheel containing an edge-weight that produces a non-linear restoring force. It is driven by a controllable motor attached to a spring. The wheel is mounted on a "smart pulley" that connects to the ULI and measures the angle of displacement.

Phase plots can be produced on the computer screen in real time and the students can see how they change in response to a change of the system's parameters. The transition to chaos can be seen, both in what it means for the real system and for how it appears in the phase space plot. Screen captures for two different sets of parameters are shown below illustrating bifurcation and the approach to chaos.

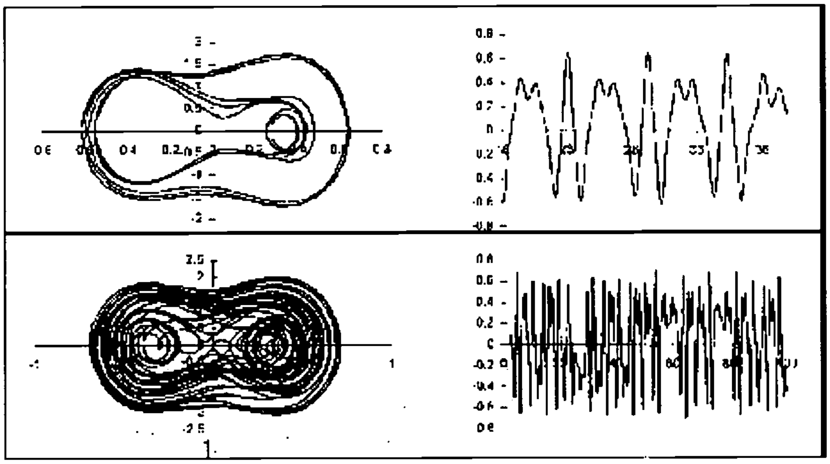

Fig. 11: Data from the chaos machine taken with two different sets of system parameters.[13]

Discovery Labs

The lab is the single item in a traditional physics course where the student is expected to be actively engaged during the class period. Unfortunately, in many cases the laboratory has turned into a place to either "demonstrate the truth of something taught in lecture" or a place to "produce a good result". The focus in both of these cases is on the content and not on what might be valuable for a student to learn from the activity. In the USA, "cookbook" laboratories -- ones in which highly explicit instructions are given and the student doesn't have to think -- are common. They are unpopular with students and tend to produce little learning. A number of interesting "guided discovery labs" have been developed in the past few years that appear to be more effective.

Tools for Scientific Thinking[14]

Ron Thornton at Tufts University and David Sokoloff at Oregon State have developed *Tools for Scientific Thinking* -- a series of guided discovery laboratories in the areas of mechanics and thermodynamics. These units focus on concept building and overcoming those student misconceptions and difficulties that researchers have found to be common. These laboratories rely on computer-data-acquisition equipment similar to that of Workshop Physics but are created as modules which can be used in a more traditional laboratory format. They make extensive use of cognitive conflict and peer interaction. Thornton and Sokoloff have done extensive research to demonstrate the effectiveness of this approach.[15] These materials are appropriate for the high school and introductory university level and focus on a conceptual rather than quantitative approach.

RealTime Physics[16]

Thornton, Sokoloff, and Laws have recently combined to develop a new series of mechanics laboratories that can be used in a traditional structure. These are similar in spirit to both Tools for Scientific Thinking and Workshop Physics. Heavy use is made of computer assisted data acquisition and the results of research on student difficulties. A more quantitative approach appropriate for calculus-based physics is developed.

Lecture Based Models

A number of interactive-engagement classes have been developed that work within the lecture format.

Peer Instruction ConcepTests[17]

Eric Mazur at Harvard University has modified his lectures by including three to four "concept tests" in each hour of lecture. After a 10-15 minute lecture segment, he presents a challenging multiple choice question to the class. This question is concept oriented and the distractors are based on the most common student difficulties as shown by research. Students answer the questions at their seats using a device that collects and displays the collective response on a projection screen, such as ClassTalk. As a result of the careful choice of question and distractors, the class usually is divided as to what they believe is the correct answer. Mazur then instructs the students to discuss the problem with their neighbor for 2-3 minutes. At the end of this period, the students answer the question again. Usually the discussion has produced a substantial improvement. If not, Mazur presents additional material.

The combination of research-based concept tests with peer interaction makes these lectures into an active-engagement environment for the student. The display of the distribution of class results may play an important role.

Interactive Demos

One recent development that may prove both effective and efficient is a series of interactive lecture demonstrations for mechanics by Thornton and Sokoloff. They have adapted their successful microcomputer-based laboratory curricula and used the results of their research into student learning to create a series of demonstrations that focus on the issues that are fundamental to student understanding of mechanics. These demonstrations are delivered to a large lecture by trained demonstrators for a few lecture periods during a semester. In order to get the students actively engaged, they have each student fill out a worksheet during the demonstration. The students are called on to make (and write down) their predictions and are led to discuss the results for a few minutes with their neighbors as in the Mazur method. Preliminary results show very strong improvement compared to normal non-interactive lecture classes.

ALPS[18]

Alan van Heuvelen at Ohio State has developed a series of worksheets for use in a large lecture format. Small bits of lecture are alternated with individual student activities and peer discussion, as in Mazur's model. This is similar in spirit to the other two lecture models discussed above but does not rely on heavy (and expensive) doses of technology.

Recitation-Based Models

Two models have obtained significant improvement in building students' conceptual understanding with a limited amount of modification of the traditional model. They only introduce interactive engagement activities in place of the recitation section, one hour per week.

Cooperative-Problem Solving

Pat and Ken Heller at the University of Minnesota and their collaborators have developed a group-learning problem-solving environment in which students work together in recitation on problems they have not previously seen.[19] These problems are "context rich", that is, they involve realistic situations, may contain incomplete data, and may require the students to pose a part of the problem themselves. The problems are intended to be too difficult for any individual student to solve. Groups are formed to include students of varying ability and students may be assigned specific (and rotating) roles to play in each group.

Recently, the Hellers have extended their method to include the laboratory and have modified some lectures to be more interactive. The combined results seem to be highly effective.[20]

Tutorials in Introductory Physics

McDermott and her group have developed a method for introducing inquiry type sessions into recitations.[21] The traditional "the instructor models problem-solving while the students watch passively" is replaced by group learning activity with carefully designed research-based worksheets. These worksheets emphasize concept building, qualitative reasoning, and make use of cognitive conflict with trained facilitators to assist in helping students resolve their own confusions.

At the University of Maryland we have developed a series of tutorials in this framework that uses the data acquisition tools of the studio classes and focuses on the use of mathematical concepts in physics. In tutorials, specific student conceptual difficulties are targeted.

The crucial element in each of these courses is that they have been developed as a result of detailed attention to student learning as well as course content. Some are associated with specific and detailed physics education research.

A Sample Evaluation:

Many of these methods have been demonstrated to be effective in improving student understanding of fundamental physics concepts. Although there is insufficient space here to discuss all the evaluation that has been done, some of the references given that describe the methods in detail also include discussions of their evaluation. I will report here on one measurement we have made testing the effectiveness of tutorials.[22] We use the Force Concept Inventory[23] (FCI) which is a 29 question multiple choice test designed to probe the students' conceptual understanding of force, dynamics, and some kinematics. It was developed on the basis of explicit and detailed physics education research. The diabolical aspect of the test is that the "distractors" (wrong answers) are the most commonly found misconceptions. Students who are confused or not confident of their understanding of Newtonian mechanics are often tempted to give one of these wrong answer.

A study[24] of the FCI given at many universities and high schools in the USA shows a systematic behavior. Courses of a similar structure (as judged on what it is the students actually do in the course) show similar "fractions of the possible gain" when the tests are given before and after instruction, despite wide initial differences between pre-test scores. The figure of merit that we use is therefore:

h = fraction of the possible gain
= (post test class average - pre-test class average)/(100 - pre-test class average)

We tested tutorials in classes of engineering physics at the University of Maryland from 1993-95. The FCI was given as pre and post-tests in ten lecture sections of first semester calculus-based physics. Five sections used tutorials, five did not. Six different professors participated in the study. The results are shown in Fig. 12. Every one of the tutorial classes scored better than every one of the non-tutorial classes. We also obtained more detailed results on the results of individual MBL tutorials on the concept of instantaneous velocity and Newton's third law.

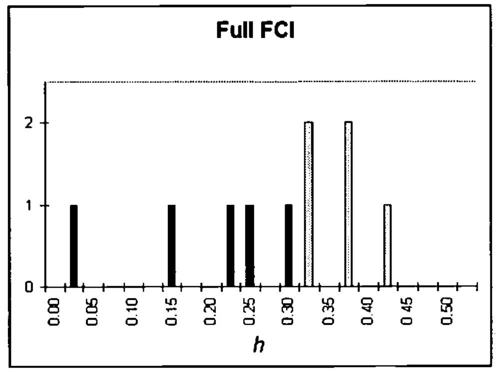

Fig. 12: Figure of merit histogram. h = fraction of the possible gain obtained on the FCI for tutorial (gray bars) and recitation (black bars) classes.

Students who had tutorials -- even only a single hour -- performed significantly better on our evaluation of their conceptual understanding of those specific topics than those students who had recitation.

Conclusion:

The growing demand that we teach physics more effectively has led to an explosion of development and innovation.

Many promising new courses will fail, as many promising educational ideas have failed in the past. Only by building a knowledge base strongly supported by evidence can we escape the draw of faddism / fashion and begin to make shared, cumulative progress.

We as physics teachers must begin to make for ourselves the "gestalt shift" to see our physics classroom in a new way. The student takes on a more "visible" role in what is happening in the classroom. The content does not diminish in importance, but the student's relation with it takes on a new and primary significance.

Acknowledgments

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[1] Edward F. Redish, "Implications of cognitive studies for teaching physics," *Am. J. Phys.* **62** (1994) 796-803.

[2] The picture is of a Dalmatian dog with head down and to the left, drinking from a puddle in the road, seen through the shadows under a leafy tree.

[3] This is taken from a greeting card created by the artist Jay Palefsky. When the card is opened, the two halves of the picture (vertically split) slide open to reveal that they are part of the larger picture as shown on the next page. See his book *Metamorphimals* (Kutzkies Artworks, Garrison NY, 1995) for a number of examples.

[4] *Hint*: The young woman's chin becomes the old woman's nose. The old woman's mouth is the young woman's necklace. (This picture is given courtesy of the Harvard-Radcliffe Cognitive Science Society, Clay Budin, Pres. It may be used at will and distributed, provided this message remains.)

[5] Howard Gardner, *Frames of Mind: The Theory of Multiple Intelligences* (Basic Books, NY, 1985); Noel Entwistle, *Styles of integrated learning and teaching: an integrated outline of educational psychology for students, teachers, and lecturers* (John Wiley, NY, 1981).

[6] Lillian C. McDermott, "Millikan Lecture 1990: What we teach and what is learned — Closing the gap," *Am. J. Phys.* **59** (1991) 301-315.

[7] This figure courtesy of Jack M. Wilson, Rensselaer Polytechnic Institute.

[8] Lillian C. McDermott et al., *Physics by Inquiry* (John Wiley and Sons, NY, 1996).

[9] Priscilla Laws, "Calculus-based physics without lectures," *Phys. Today* **44**:12 (1991) 24-31; Priscilla Laws, *Workshop Physics* (Vernier Software, Portland OR, 1995).

[10] Jack M. Wilson, "The CUPLE Physics Studio", *The Physics Teacher* **32** (1994) 518-529.

[11] Vernier Software, Portland OR.

[12] The chaos machine is currently available from Pasco.

[13] Data taken by Bao Lei, University of Maryland.

[14] David R. Sokoloff and Ronald K. Thornton, *Tools for Scientific Thinking* (Vernier Software, Portland OR, 1992 and 1993).

[15] Ronald K. Thornton, "Conceptual Dynamics: Changing Student Views of Force and Motion," in C. Tarsitani, C. Bernardini and M.Vincentini, (Eds.) *Thinking Physics for Teaching* (Plenum, 1995).

[16] Priscilla Laws, David R. Sokoloff and Ronald K. Thornton, *RealTime Physics* (Vernier Software, Portland OR, 1995).

[17] Eric Mazur, *Peer Interaction, A User's Manual* (Prentice Hall, 1996).

[18] Alan Van Heuvelen, *ALPS: Mechanics (Vol. 1), Electricity and Magnetism (Vol. 2)* (Hayden-McNeil Publishing, Westland MI, 1994)

[19] Patricia Heller, Ronald Keith, and Scott Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," *Am. J. Phys.* **60**:7 (1992) 627-636; Patricia Heller, and Mark Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," *Am. J. Phys.* **60**:7 (1992) 637-644.

[20] Ken Heller, private communication, January 1996.

[21] Lillian C. McDermott, Peter S. Shaffer, and Mark D. Somers, "Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwoods's machine," *Am. J. Phys.* **62** (1994) 46-55.

[22] Edward F. Redish, Jeffery M. Saul, and Richard N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories", University of Maryland preprint, to be published.

[23] David Hestenes, Malcolm. Wells, and Gregg Swackhammer, "Force Concept Inventory," *The Physics Teacher* **30**:3 (1992) 141-158.

[24] Richard Hake, "A five-thousand-student survey of mechanics test data for introductory physics courses", Indiana University preprint, to be published.

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