Understanding or memorization: Are we teaching the right thing?

Eric Mazur

Department of Physics, Harvard University, Cambridge, MA 02138, USA

When people I meet ask me what I do for a living and I tell them I am a *physicist*, I frequently hear horror stories about high school or college level physics — almost to the point of making me feel embarrassed about being a physicist! This general sense of frustration with introductory physics (mechanics, electricity and magnetism) is widespread among non-physics majors who are required to take physics courses. Even physics majors are frequently dissatisfied with their introductory courses and a large fraction of students initially interested in physics end up majoring in a different field.

Frustration with introductory physics courses has been commented on since the days of Maxwell and has recently been publicized by Sheila Tobias.[1] Tobias asked a number of graduate students in the humanities and social sciences to audit physics courses and describe their complaints. One may be tempted to brush off complaints by non-physics majors as coming from students who are *ipso facto* not interested in physics. Most of these students, however, are *not* complaining about other required courses outside their major field.

The way physics is taught in the 1990's is likely not much different from the way it was taught — to a much smaller and more specialized audience — in 1890. The basic approach of introductory physics textbooks has not changed in over one hundred years, yet the audience has. Physics has become a building block for many other fields including chemistry and the engineering and life sciences. As a result, the enrollment in physics courses has grown enormously, with the majority of students not majoring in physics. This shift in constituency, from physics majors with an interest in the subject to

---

[1] Sheila Tobias, *They're not Dumb, They're Different: Stalking the Second Tier* (Research Corporation, Tucson, AZ 1989).

non-physics majors required to take physics — 'captives' as Richard Crane calls them[2], has caused a significant change in student attitude towards the subject and made the teaching of introductory physics a considerable challenge. While traditional methods of instruction have produced many successful scientists and engineers, far too many students are unmotivated by the conventional approach. What, then, is wrong with the traditional approach to introductory physics?

For the past nine years I have been teaching an introductory physics course for engineering and science majors at Harvard University. Until a number of years ago I taught a fairly traditional course in an equally traditional lecture-type of presentation, enlivened by classroom demonstrations. I was generally satisfied with my teaching during these years — my students did well on what I considered difficult problems and the response I received from them was very positive.[3] As far as I knew there were not many problems in *my* class.

A number of years ago, however, I came across a series of articles[4] by David Hestenes of Arizona State University, which, to put it bluntly, 'opened my eyes'. In these articles, Hestenes shows that students enter their first physics course possessing strong beliefs and intuitions about common physical phenomena. These notions are derived from personal experiences, and color students' interpretations of material presented in the introductory course. Hestenes' research shows that instruction does very little to change these 'common-sense' beliefs.

For example, after a couple of months of physics instruction, all students will be able to recite Newton's third law — 'action is reaction' — and most of them can apply this law in numerical problems. A little probing beneath the surface, however, quickly shows that many of these students lack fundamental understanding of the law. Hestenes provides many examples in which the students are asked to compare the forces of different objects on one another. When asked, for instance, to compare the forces in a collision between a heavy truck and a light car, a large fraction of the class firmly believes the heavy truck exerts a larger force on the light car than vice versa. When reading this, my first reaction was 'Not *my* students…!' Intrigued, I nonetheless decided to test my own students' conceptual understanding, as well as that of the physics majors at Harvard.

The first warning came when I gave the test to my class and a student asked 'Professor Mazur, how should I answer these questions? According to what you taught us, or by the way I *think* about these things?' Despite this warning, the results of the test came as a shock: the students fared hardly better on the Hestenes test than on their midterm

---

[2] H. Richard Crane, *Am. J. Phys.* 36, 1137 (1968).

[3] My ratings on the Harvard Committee on Undergraduate Education questionnaires have consistently been among the highest in the Physics Department at Harvard.

[4] Ibrahim Abou Halloun and David Hestenes, *Am. J. Phys*, 53, 1043 (1985); *ibid*. 53, 1056 (1985); *ibid*. 55, 455 (1987); Hestenes, David, *Am. J. Phys*, 55, 440 (1987).

examination on rotational dynamics. Yet, the Hestenes test is *simple* — yes, probably too simple to be considered seriously for a test by some colleagues — while the material covered by the examination (rotational dynamics, moments of inertia) was, so I thought, of far greater difficulty.

I spent many, many hours discussing the results of this test with my students one-on-one. My previous feeling of satisfaction with my teaching accomplishments turned more and more into sadness and frustration. How could these undoubtedly bright students, capable of solving complicated problems, fail on these ostensibly 'simple' questions?

To understand these seemingly contradictory facts, I decided to pair, on the students' remaining examinations, 'simple', qualitative questions with more 'difficult', quantitative problems on the same physical concept. Much to my surprise some 40% of the students did *better* on the quantitative problems than on the conceptual ones — on the subject of dc-circuits half a dozen even managed to receive *full marks* on a complex quantitative problem involving a two-loop circuit while getting *zero* points on a related 'simple' conceptual question! Slowly, the underlying problem revealed itself: many students concentrate on learning 'recipes', or 'problem solving strategies' as they are called in textbooks, without considering the underlying concepts. Plug and chug! Many pieces of the puzzle suddenly fell into place. The continuing requests by students to do more and more problems and less and less lecturing — isn't this what one would expect if students are tested and graded on their problem solving skills? The unexplained blunders I had seen from apparently 'bright' students — problem-solving strategies work on some, but surely not on all problems. Students' frustration with physics — how boring physics must be when it is reduced to a set of mechanical recipes that do not even work all the time! And yes, Newton's third law is second nature to me — it's *obviously* right, but how do I convince my students? Certainly not by just reciting the law and then blindly using it in problems… After all, it took mankind thousands of years to formulate the third law.

Before I had been oblivious to this problem. By the traditional measures — quantitative problem skills and student feedback — I had been fooled into believing that I was succeeding in teaching and that the students were succeeding in learning introductory physics. Now the picture looked quite different. While several leading physicists have written on the students' lack of fundamental understanding,[5] I believe many are still unaware of the magnitude of the problem — as I was until just a few years ago.

An important problem with the conventional teaching method is that it favors problem solving over conceptual understanding. As a result, many students memorize 'problem solving strategies'; for these students introductory physics becomes nothing more than problem solving by rote and little understanding of the fundamental principles is gained. This practice of memorizing algorithms and equations without understanding the con-

---

[5] See for example: Arnold Arons, *A Guide to Introductory Physics Teaching* (John Wiley & Sons: New York, NY, 1990); Richard P. Feynman, *The Feynman Lectures*, Vol. 1, (Addison Wesley, New York, N.Y., 1989) p. 1-1; Ken Wilson., *Phys. Today* **44:9** (1991) p. 71-73.

cepts behind the manipulations is intellectually unrewarding and results in poor student performance and frustration with the material. And what good is it to teach just the mechanical manipulation of equations without achieving understanding?

Another problem lies in the presentation of the material. Frequently, it comes straight out of textbooks and/or lecture notes, giving the students little incentive to attend class. The fact that the traditional presentation is nearly always in the form of a monologue in front of an entirely passive audience compounds the problem. Only exceptional lecturers are capable of holding students' attention for an entire lecture period. It is even more difficult to provide adequate opportunity for the students to *critically think* through the arguments being developed and in introductory classes few students have the motivation and the discipline to do this on their own after class. Consequently, the lectures only reinforce the students' feeling that the most important step in mastering the material is solving problems. One ends up in a rapidly escalating loop whereby the students will request more and more example problems (so they can learn better how to solve them), which in turn further reinforces their feeling that the key to success is problem solving.

In the past three years I explored new approaches to teaching introductory physics. In particular, I was looking for ways to refocus students' attention on the underlying concepts without sacrificing the students' ability to solve problems. During this period of time, I developed a method of teaching, called *Peer Instruction*[6] which I'll describe in the remainder of this paper. It has become clear that *Peer Instruction* is very effective in teaching the conceptual underpinnings in introductory physics and leads to better student performance on traditional problems. This has been verified not only at Harvard University, but also in a number of other schools, ranging from state schools, to liberal arts colleges, to military academies. Most interestingly, I have found it makes teaching easier and more rewarding.

Peer Instruction: getting students to think in class

The basic goal of the method is to exploit student interaction in class and to focus the students' attention on underlying concepts. Instead of presenting the material sequentially (as it is in the textbook and in the notes), lectures consist of a number of short presentations of the key points of the material, each followed by a so-called *ConcepTest* — a short multiple-choice conceptual question on the subject being discussed. The students are first given some time to formulate an individual answer, and then asked to discuss their answers with each other in the classroom. This process *a*) forces the students to critically think through the arguments being developed and *b*) provides them (as well as the teacher) with a way to assess their understanding of the concept.

---

[6] See *e.g.* Chapter 8 in *Revitalizing Undergraduate Science: Why Some Things Work and Most Don't* by Sheila Tobias (Research Corporation, Tucson, AZ, 1992).

The students' answers to the *ConcepTests* also provide a continuous assessment of the students' understanding of the material *during* the class. If the students' performance on the *ConcepTest* is satisfactory, the lecture can proceed to the next topic. Else, the teacher should slow down, lecture in more detail on the same subject, and re-assess the students with another *ConcepTest* on that subject. This prevents a gulf from developing between the teacher's expectations and the students' understanding — a gulf, which once formed, only increases with time until the entire class is 'lost'.

Table 1 shows an outline for a lecture introducing three or more new concepts. Notice how the students' understanding of each concept is verified with at least one *ConcepTest* after approximately 10 minutes of lecturing. Each of these has the general format outlined in Table 2. The total duration of a single lecturing–*ConcepTest* cycle is approximately 15 minutes. Central to the entire method, therefore, is a set of simple qualitative questions for the *ConcepTests*, each dealing with a *single* fundamental concept. These questions help focus the students' attention on understanding *before* problem-solving. In the traditional approach to introductory physics, on the other hand, understanding is assumed to follow from mechanically working problems.

Let's consider for a moment a specific example — a lecture on fluids. Suppose the concept we want to get across is that of Archimedes' principle. We first lecture for about 7-10 minutes on the subject of Archimedes' principle — emphasizing the concepts and the ideas behind the proof and avoiding (or even omitting) any equations and derivations. This short lecture period could include a demonstration (the Cartesian diver, for instance). Then, before going on to the next topic (Pascal's principle, perhaps), we project the following multiple-choice question[7] (step 1):

> Consider a bathtub brimful of water. Next to it is a second, identical bathtub, also brimful of water, but with a battleship floating in it. Which one weighs more?
>
> 1. A bathtub brimful of water
> 2. A bathtub brimful of water with a battleship floating in it
> 3. Both weigh the same

It is important to read the question with the students and to make sure there are no questions as to the precise meaning of the question itself (strange as this may sound!). Next, we tell the students that they have one minute to come up with an answer — more time would allow the students to fall back onto equations and manipulate equations rather than *think*. It is now silent in the class-room as the students concentrate on the question (step 2). After about a minute we ask the students to record their answer (step 3; see also Appendix 2), and then to try to convince their neighbors of their answers. The silence turns into chaos as *everyone*, intrigued by the question, tries to argue with surrounding neighbors (step 4). After giving the students a minute to argue, we ask them to record a revised answer (step 5). Then we go back to the overhead and ask for a show

---

[7] This question is from Lewis Carroll Epstein, *Thinking Physics*, Insight Press, San Francisco (1990).

of hands to see how many selected the various answers. I use the above question in my own class; the results are shown in Fig. 1.

Notice that 78% of the students got the correct answer before discussion and 88% after discussion. The pie charts show another benefit of the discussion periods: the fraction of students who are ‘pretty sure’ of their answer increases from 56% to 81%. Of course, I did not have access to such detailed results in class, but the show of hands would have revealed an overwhelming majority of correct answers. I would therefore have spent only a few minutes explaining the correct answer before going on to the next topic.

The increase in the number of correct responses and the students’ confidence is frequently much more pronounced than in the example shown in Fig. 1.[8] Repolling the students’ responses after the *Peer Instruction* periods systematically reveals a strikingly greater proportion of correct answers. It seems that the students are able to explain concepts to one another more efficiently than are their instructors, for whom such concepts are second nature. The students who understand the concepts when the question is posed, on the other hand, have only recently mastered the idea. Because of this, they are still aware of the difficulties one has in grasping that particular concept. Consequently, they know precisely what to emphasize in their explanation. Similarly, many seasoned lecturers know that their first presentation of a new course is often their best. Their initial presentation of the material is marked by a clarity and freshness often lacking in the more ‘polished’ version. The underlying reason is the same: as time passes and one is continuously exposed to the material, the conceptual difficulties seem to disappear.

In this new lecturing format, the *ConcepTests* take about one third of the total time in each lecture. This necessarily means that less time is available for straight lecturing. One therefore has two choices: (*a*) discuss only part of the material in the lectures, or (*b*) reduce the overall coverage of the material in the course. While (*b*) may eventually be the preferable choice, I have opted for choice (*a*). I do not cover all the material in class — after all, the details are always available in the book or in the notes. I start by throwing out nearly all derivations and *all* example problems (yes, that’s right). As I have argued, students derive precious little benefit from seeing the instructor manipulate equations anyway. To make up for the omission of these more mechanical aspects of the course, I *require* the students to *read* the material ahead of the class. While this may sound surprising for a science course, students are accustomed to reading assignments in many other courses. In this way I can continue to cover the same amount of material as before. Moreover, the students’ attention is focused more strongly on the underlying principles. The students still get the opportunity to learn problem solving in weekly sections, half of which are devoted to developing problem skills. In addition, the home assignments consist half of traditional problems, half of essay type questions.

---

[8] The improvement is usually largest when the initial percentage of correct answers is about 50%. If it is much higher (as in the case of Fig. 1), there is little room left for improvement. If it is much lower, there are too few students in the audience who are able to convince others of the correct answer. See also Fig. 5.

Results

Before getting into the specifics and providing more detailed guidelines on the implementation of *Peer Instruction*, let me first summarize some of the results I have obtained with this method in my course. Results, I should emphasize, that are supported by findings from other institutions where *Peer Instruction* has been implemented.[9]

The advantages of *Peer Instruction* are numerous. The discussion periods break the unavoidable monotony of passive lecturing. Not only are the students kept alert, but they are actively involved in the lecture. I have found that the discussions among the students are always remarkably uninhibited and animated. Furthermore, the students do not merely assimilate the material presented to them; they must think for themselves and put their thoughts into words. The data collected over the past three years demonstrate that following the *Peer Instruction* periods, student confidence as well as the proportion of correct answers increases dramatically and systematically.

The long-term gains are even more striking. In the past few years I have used a diagnostic test, the *Force Concept Inventory* developed by Hestenes,[10] to test student understanding of the underlying concepts. This test has been utilized in a number of studies across the country to determine the effectiveness of physics instruction. Data obtained in my class in 1990 and 1991 allows one to compare the relative effectiveness of the *Peer Instruction* and the traditional approaches. The results are shown in Figs. 2 and 3. Figure 2 shows a dramatic improvement in student performance using the *Peer Instruction* method. After instruction, only 4% of the students are below the cutoff identified by Hestenes as the threshold for the understanding of Newtonian mechanics. Notice also how the scores are strongly shifted towards full marks (29 out of 29). Conversely, with the traditional approach used the year before (1990), the improvement was much smaller, in agreement with what Hestenes has found at other institutions.

While the improvement in conceptual understanding is undeniable, one might question how effective the new approach is in teaching the problem solving skills required on traditional examinations. After all, the restructuring of the lecture and its emphasis on conceptual material is achieved at the expense of time devoted to problem solving. To answer this question, I gave the *identical* final examination in 1991 as the one I gave in 1985. Figure 4 shows the distributions of final examination scores for the two years. Given the students' improvement in conceptual understanding, I would have been satisfied if the distributions were the same. Instead, there is actually a marked *improvement* in the mean, as well as a higher cut-off in the low-end tail.

---

[9] See Sheila Tobias, *Revitalizing Undergraduate Science Education: Why Some Things Work and Most Don't,* Research Corporation: Tucson, AZ (1992).

[10] D. Hestenes, M. Wells, G. Swackhamer, The Physics Teacher 30, 141 (1992)

Converting lectures from the old to the new format

Below I will attempt to describe what I have done with my own material over the past few years to change from a traditional lecturing style to *Peer Instruction*. I should stress that I still use my old lecture notes — it is not necessary to completely rewrite one's lecture notes! I hope this description will therefore serve as a guide for converting your own material for use with *Peer Instruction*.

1. *Reading assignments*. Since the *ConcepTests* take time away from the lecture, it will not be possible to devote as much time to straight lecturing as before. As I mentioned, I have *completely* eliminated all worked sample problems and many derivations from my lecture. Even though this may come as a surprise to many, the literature abounds with indications that students derive little or no benefit from seeing someone solve a problem. Besides, the results shown above indicate that the students' ability to solve problems is not affected by the omission of examples and/or derivations.

I tell the students on the first day of class that I will not lecture straight out of my notes or out of the textbook and that I *expect* them to read the relevant material (notes and book) in advance. To make sure they actually carry out their reading assignments, I provide them with some incentive.[11] As a result, I am still able to cover the same amount of material as before implementing *Peer Instruction*.

In fact, at the first lecture I distribute a schedule of lectures that provides the students with a reading assignment for the entire semester, and I stick *religiously* to the schedule — better than I ever was able to do before. If a certain lecture goes faster than anticipated (a rare event), the students get an early break; nobody is unhappy. If a certain lecture goes slower than planned (usually because a *ConcepTest* revealed some difficulty with the material), I skip the less important part(s) and rely on *a*) the students' reading, *b*) sections (weekly discussion sessions), and *c*) homework assignments. In some cases, I may use part of the next lecture to stress some important points or to give an extra *ConcepTest*. In any case, I always plan a single review lecture in the middle of the semester to allow for some slack in an otherwise very rigid schedule. So the flexibility is in the schedule of the individual lecture, not that of the semester.

A key point is thus to get the students to do part of the work ahead of time. Unfortunately most books are not ideal; they provide so much information that the student is usually unable to determine what is relevant and what is not. Part of the reading is therefore from the lecture notes.

---

[11] At the beginning of the class, I give the students a special *ConcepTest* called a *Bonus Question* which allows the students to earn some credit towards their final grade. This question differs from the others in that the material is not first discussed and requires the students to have *read* the material before coming to class. In addition, the responses are collected immediately and the students do not discuss the answers with one another.

2. *Key concepts*. In some lectures, taking away examples and derivations leaves surprisingly little material. This, however, is the 'core' material of the lecture which contains the key concepts. After taking the derivations and worked example problems out of my presentation, the next thing I do is to determine what the four or five key points are that I want to get across to the students. I also frequently consult Arnold Arons' book *A Guide to Introductory Physics Teaching* for additional advice on where to expect the most difficulties. Eventually I am left with a skeletal lecture outline consisting of four or five key points (see Table 3).

3. *ConcepTests.* At this point, it is important to develop a number of good conceptual questions to test understanding of each of the key concepts in the above lecture outline. This constitutes perhaps the largest amount of work in converting the lecture. The importance of this task should not be underestimated — the success of the method depends to a large extent on the quality and the relevance of these questions. Sources for (inspiration for) such questions are listed in the next section.

While there are no hard and fast rules for the *ConcepTests*, they should at least satisfy a number of basic criteria. Specifically, they should

1) focus on a single concept,
2) not be readily solvable by relying on equations,
3) have adequate multiple choice answers,
4) be unambiguously worded, and
5) be neither too easy nor too difficult.

The first three of these points are the most important because they directly affect the feedback of information to the instructor. If more than one concept is involved in the question, it will be more difficult to interpret the results of the question and correctly gauge the students' understanding. Similarly, if the students can derive the answer by relying on equations, then the students' responses will not adequately reflect their real understanding. The choice of answers provided is another important point. Ideally, the incorrect answers should reflect the students' most common misconceptions. At present, the incorrect answers to each *ConcepTest* have been formulated with this criterion in mind, but the ultimate source for the alternative responses ('detractors') should be the students themselves. For instance, by posing the question in a 'fill-in' format and then tallying the most prevalent incorrect responses, a student-generated *ConcepTest* question accurately mirroring common misconceptions could be generated.

The last two points are harder to gauge beforehand, even though they may sound entirely unmistakable. I have been surprised time and again to see that questions that appeared to be completely straightforward and unambiguous to me, were misinterpreted by many students. These ambiguities can only be eliminated by class-testing questions. As for the level of difficulty, Fig. 5 shows the percentage of correct answers after discussion versus that before discussion for all questions during a full semester. Notice that *all* points lie above a line of slope 1 (points on or below that line would correspond to an entirely useless discussion). As should be expected, the improvements are largest when the initial percentage of correct answers is around 50% (with jumps as large as from 40 to 90%). I consider an initial percentage of correct responses in the 50 to 80% range optimal.

4. *Lecture plan*. Once the questions are made up, I take a new look at my old lecture notes and decide at what point in the remaining material to put the newly made questions. At the same time, I plan which lecture demonstrations to give. Sometimes I may even combine a question with a demonstration, with one leading into the other.

5. *Lecture*. The actual lecture is much less 'rigid' than before. It is necessary to keep a certain amount of flexibility to respond to the sometimes unexpected results of the *ConcepTests*. I find myself improvising more often than before. While this may seem like a disturbing prospect at first, I should say that the added flexibility actually makes the teaching *easier* than before. During the periods of silence (when the students are thinking) I get a break — a minute or so to catch my breath and to reformulate my thoughts. During the periods of discussion, I usually participate in some of the discussion to get a feel for what goes on in the mind of the students. This helps me to focus better on the problems the students are facing and keeps me 'in touch' with the class.

I should also mention that the new lecture format elicits more questions from the students than I have ever encountered before. Often these questions are very to the point and profound, and I attempt to address as many of them as I can.

Conclusion

So, with relatively little effort and no capital investment it is possible to greatly improve student performance in introductory science courses. To achieve the results reported above, I merely incorporated a number of conceptual questions into each lecture. For the remainder of my lectures I used my existing lecture notes. I omitted worked-out examples and derivations, assigning these as reading to the students. Despite the reduced time devoted to problem solving, the results convincingly show that conceptual understanding enhances student performance on traditional type examinations. Finally, student surveys show that student satisfaction — an important indicator of student success — is greatly increased.

Appendix 1: Sources for ConcepTests

Creating and compiling conceptual problems is an important task, since the *ConcepTests* are central to the success of the method. To make this task easier, I hope to develop an informal network of people sharing such questions with one another. Over the course of the past two years we have developed questions for all concepts covered in introductory physics.[12]

There are a number of good sources of both questions and inspiration. End-of-chapter *questions* (as opposed to 'problems' or 'exercises') in most standard introductory physics texts can be a useful starting point. The *American Journal of Physics* publishes many articles which may prove helpful in creating new *ConcepTests*. In addition, the books listed below emphasize fundamental concepts and contain numerous questions which are designed to both isolate these concepts, and to help students grasp them by exposing their most common misconceptions about the material. This list is not comprehensive, but represents the sources I have most frequently drawn from myself.

Arnold B. Arons, *A Guide to Introductory Physics Teaching*, John Wiley & Sons, New York (1990).

Lewis Carroll Epstein, *Thinking Physics*, Insight Press, San Francisco (1990).

Paul G. Hewitt, *Conceptual Physics*, Scott, Foresman and Company, Boston (1989).

Jearl Walker, *The Flying Circus of Physics*, John Wiley & Sons, New York (1977).

---

[12] Typically between two and five fundamental concepts are introduced each lecture, for a total of about 150 for a standard introductory physics text. We have developed complete sets of questions and obtained detailed statistics on student performance for each of these. They are available upon request.

Appendix 2: Feedback methods

One of the great advantages of *Peer Instruction* is that it provides immediate feedback on the level of student understanding; however, it requires that one keeps track of the students' answers to the *ConcepTests*. The tallying of these answers can be accomplished in a variety of ways, depending on the setting and purpose. Three methods that we have used are:

1. Show of hands
2. Scanning forms
3. Hand-held computer devices

The simplest method of data collection is a show of hands after the *Peer Instruction* periods. This method does not require any new technology or investment, but will still accomplish the goals of *Peer Instruction*. It will give a feel for the level of the class' understanding and allows the teacher to tailor the pace of the lecture accordingly. The only drawback is a certain loss of accuracy, in part because some students may hesitate to raise their hands, and in part because of the difficulty in estimating the distribution of answers. Another minor problem is the lack of a permanent record (unless one keeps data in class) and the lack of any data *before* the *Peer Instruction* discussion.

Since I was interested in actually quantifying the effectiveness of the *Peer Instruction* discussion both on the short and the long term, I have made extensive use of forms that were scanned after class. On these forms, which are reproduced on pages 50–51, the students mark their answers and the confidence they have in these answers, both before and after discussion. This method yields an enormous body of data on students' attendance, understanding, improvement, and on the short-term effectiveness of the *Peer Instruction* periods. The drawback of this method, however, is that it is labor intensive and that there is a delay in the feedback: the data are available only after the forms are scanned. For this reason, I always ask for a show of hands (in addition to requiring the students to mark their answers).

A year ago we installed an interactive computer response system called *ClassTalk*, produced by *Better Education, Inc*. The system allows the students to indicate their answers to the *ConcepTests*, as well as their confidence levels, on hand-held computers which they can share in small groups of three or four. Their responses are relayed to the instructor on a computer screen and can be projected so the students can see it too. The main advantage of the system is that the analysis of the results is available immediately. There are many additional features and advantages: student information (such as the students' name and seat location) is also available, making large classes more personal; the system can also handle numerical and non-multiple choice questions; we have also found that sharing of these handheld computers enhances the student interaction. Potential drawbacks are that the system requires a certain amount of capital investment and that it adds complexity to the lecture.

Figure Captions

Fig. 1 Data analysis of the *ConcepTest* about Archimedes principle shown in the text. The students' initial responses and confidence levels are displayed on the left; the students' revised post-discussion responses and confidence levels are displayed on the right. The lower left graph shows how students changed their mind as a result of the discussion.

Fig. 2 Histograms of scores on the *Force Concept Inventory* test obtained in 1991 on the first day of class (left) and after two months of instruction with the *Peer Instruction* method (right). The maximum score on the test is 29 (out of 29). The means of the distributions are 19.8 and 24.6.

Fig. 3 Histogram of scores on the *Force Concept Inventory* test obtained in 1990 after two months of traditional instruction (right). For comparison, data obtained on the first day of class in 1991 are shown on the left. The means of the distributions are 19.8 and 22.3.

Fig. 4 Histograms of final examination scores in 1985 (left) and 1991 (right). In both cases the examination was the same. In 1985 the course was taught in a traditional manner; in 1991 the method of *Peer Instruction* was used. The means of the distributions are 62.7 and 69.4 out of 100 points maximum in 1985 and 1991, respectively.

Fig. 5 Percentages of correct responses after discussion versus that before discussion (left) and the same information weighted with the students' confidence.

1.	Lecture on concept 1 (including demos, etc.)	7-10 minutes
	ConcepTest 1: do students understand concept 1?	5 minutes
	If no: back to square 1!	varies
	If yes: continue	
2.	Lecture on concept 2 (including demos, etc.)	7-10 minutes
	ConcepTest 2: do students understand concept 2?	5 minutes
	If no: back to square 2!	varies
	If yes: continue	
3.	Lecture on concept 3 (including demos, etc.) *etc. etc.*	

Table 1. General outline for a lecture introducing three (or more) new concepts. An outline for each *ConcepTest* is shown in Table 2.

1.	A simple conceptual question is posed	1 minute
2.	Silence: the students are given time to think	1 minute
3.	Students record their answers (optional)	
4.	Chaos: the students are asked to ‘convince’ their neighbors	1 minute
5.	Students record their answers (optional)	
6.	Feedback to instructor: Tally of answers	
7.	Explanation of answer to question	2+ minutes

Table 2. Format of a single *ConcepTest*.

1. definition of pressure
2. pressure as a function of depth
3. Archimedes’ principle
4. Pascal’s principle

Table 3. Outline for a lecture on fluid statics

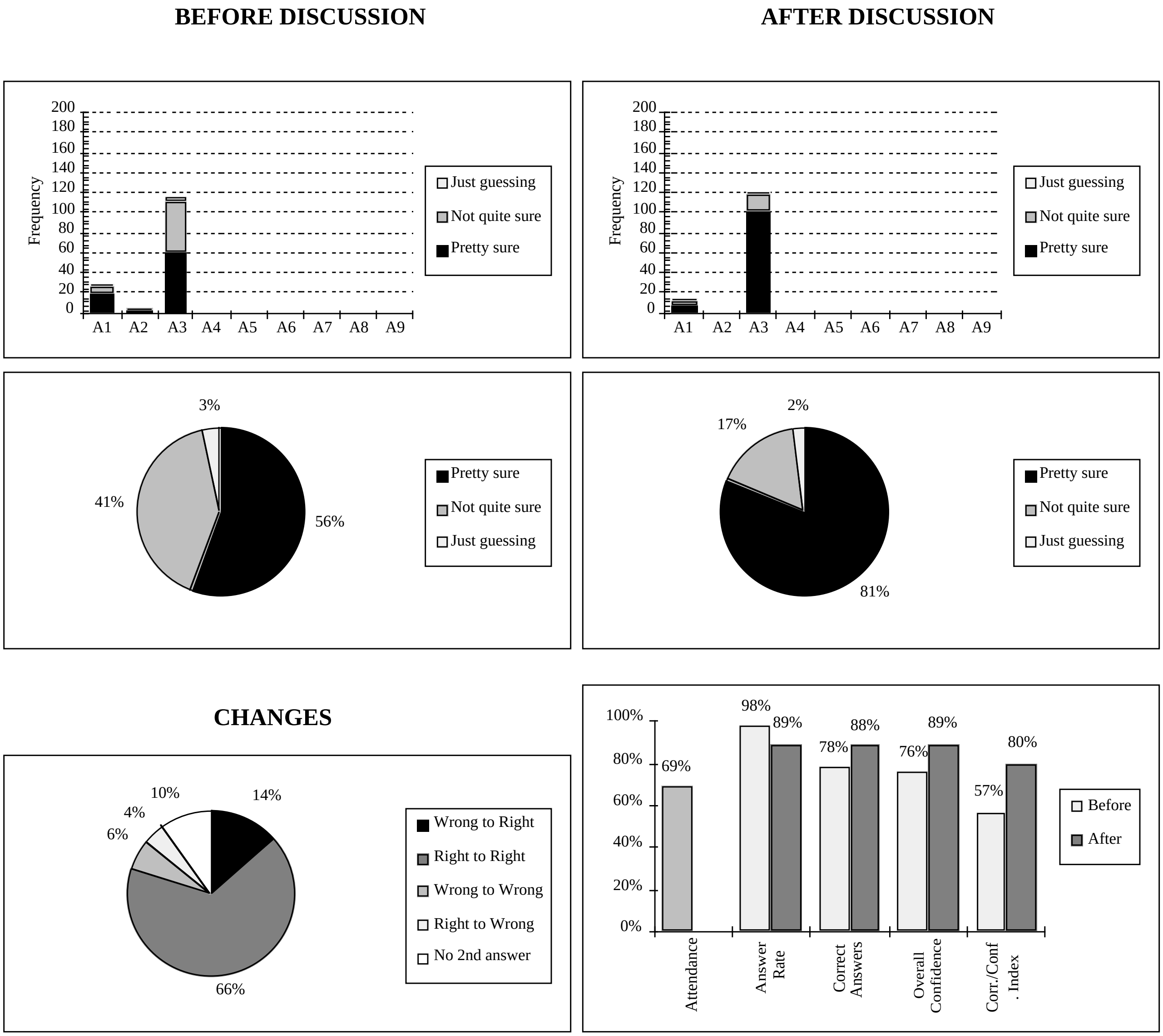BEFORE DISCUSSION
AFTER DISCUSSION
Frequency
200
180
160
140
120
100
80
60
40
20
0
A1
A2
A3
A4
A5
A6
A7
A8
A9
Just guessing
Not quite sure
Pretty sure
3%
41%
56%
2%
17%
81%
CHANGES
10%
14%
4%
6%
66%
Wrong to Right
Right to Right
Wrong to Wrong
Right to Wrong
No 2nd answer
100%
80%
60%
40%
20%
0%
69%
98%
89%
78%
88%
76%
89%
57%
80%
Attendance
Answer Rate
Correct Answers
Overall Confidence
Corr./Conf. Index
Before
After

Figure 1

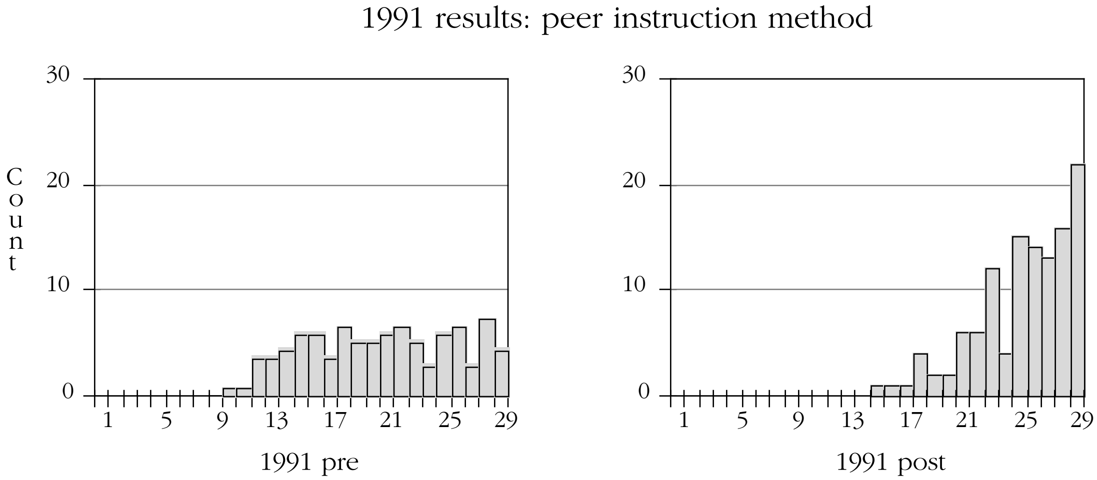

Figure 2

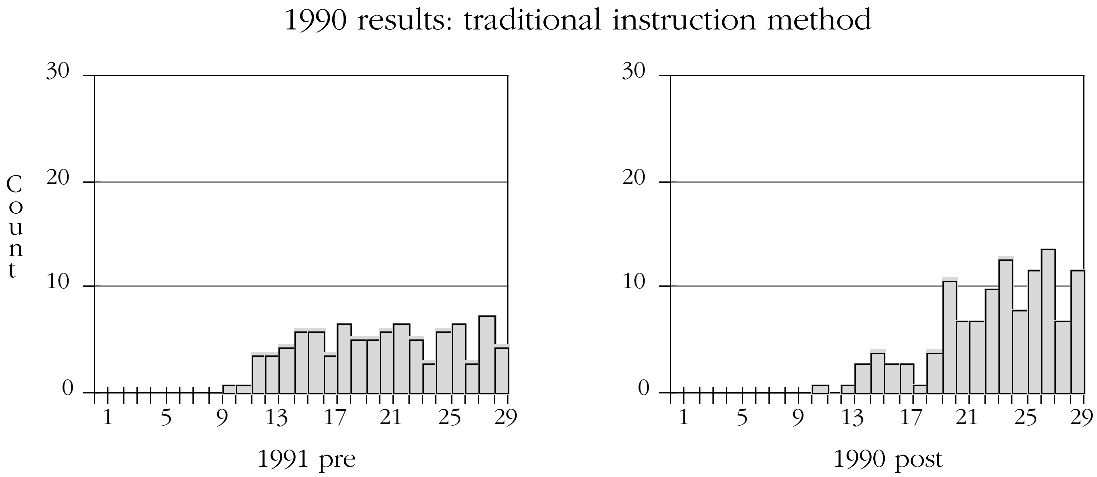

Figure 3

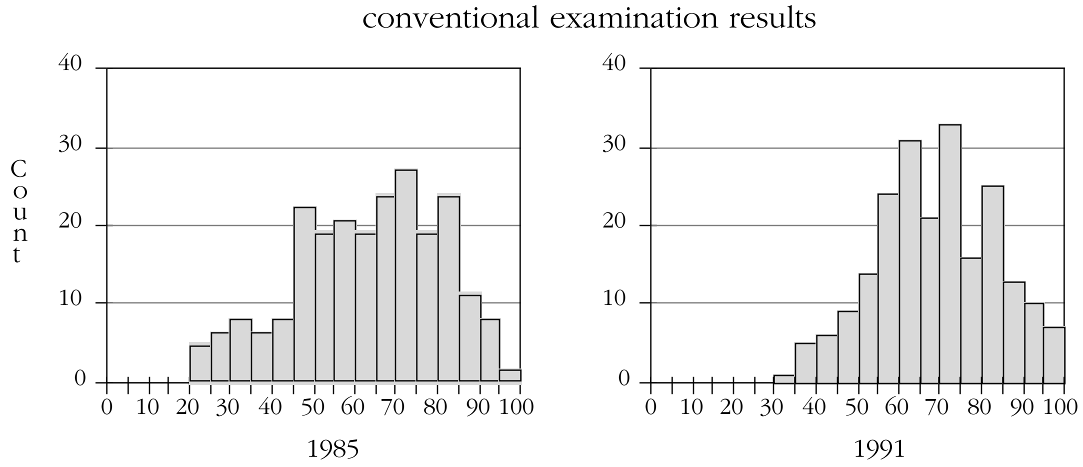

Figure 4

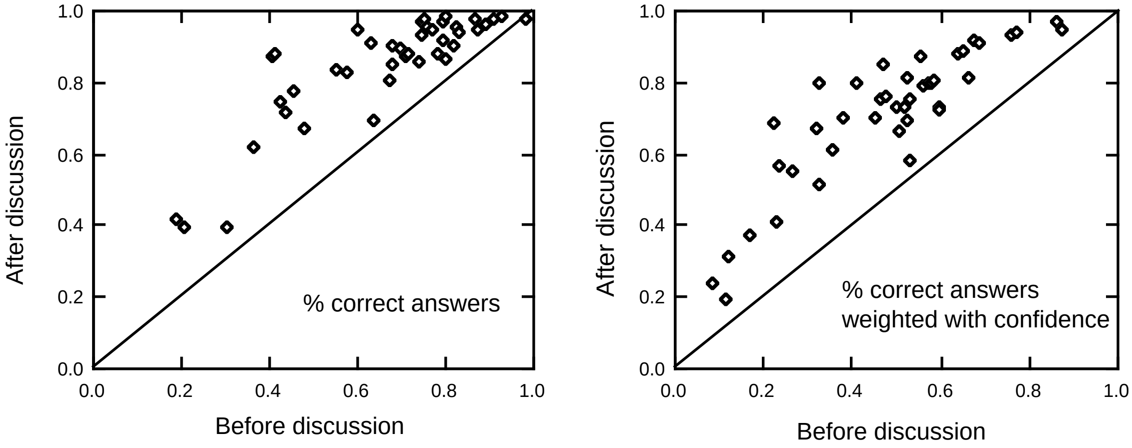

Figure 5