PEER LEARNING IN THE LARGE-LECTURE SETTING

by Alan J. Slavin

There is now a large body of published research that shows which approaches to physics teaching are most successful. In particular, the learning that takes place with student-student interaction has been shown to be superior to that from a traditional lecture approach, even for instructors who are recognized as being excellent lecturers. This paper reviews several peer-learning approaches, with a full discussion on the use of Peer Instruction for large classes in a "lecture" hall. It includes a survey of interactive teaching in Canadian universities today.

The learning that takes place with student-student interaction has been shown to be superior to that from a traditional lecture approach, even for instructors who are recognized as being excellent lecturers.

INTRODUCTION

A revolution in undergraduate physics teaching is underway, evolving from research that started in the 1970's when some physics instructors questioned the efficacy of the standard lecture approach. Arnold Aarons in particular (Ref. 1 and references therein), raised serious concerns about the backgrounds of most students studying introductory physics, questioning whether they had even the basic understanding of fundamental concepts such as area, volume and proportion required to appreciate very simple physics concepts. This work led to a systematic study by other researchers.

The commitments of university professors for teaching, scientific research, and administration leaves little time for a serious examination of their own teaching effectiveness. Moreover, traditional measures of student performance are not good indicators, as numerous studies have shown that students can perform quite well with numerical problems without really understanding the material at a conceptual level; they have only memorized approaches that lead them to the correct numerical answers. Finally, there is even some evidence [2] that course-faculty evaluations by students are modified by the degree to which instructors empathize with students, rather than cleanly measuring how well students think they understand the subject.

Happily, there are now several universities with Physics Education Research groups that undertake such studies as their primary academic research, including those at the University of Washington, Seattle [3], Harvard [4], and the University of Maryland [5]. They have carried out statistical studies, with control groups, to evaluate the usefulness of one approach over another. This greatly simplifies the task of the physics professor, who can now go to the literature to find approaches that have been proven to be effective. Most physics faculty would never dream of beginning a new direction in scientific research without carrying out a literature search. However, it is surprising how many professors seldom look at the available information on teaching effectiveness.

This article addresses the teaching of large classes in a lecture-type setting. It begins with a review of the main results from the physics education research, followed by practical suggestions for the implementation of "Peer Instruction" as used at Trent University for several years, and ends with a survey of interactive approaches currently employed at Canadian universities. The article concentrates on the conceptual understanding of physics. Other skills, such as the ability for problem solving and experimental skills, are obviously important but beyond the scope of this article except insofar as a strong conceptual understanding is a prerequisite for being more than superficially successful in the other areas.

SUMMARY OF RESULTS FROM PHYSICS EDUCATION RESEARCH

The conclusions of much of the physics education research have been summarized by McDermott [6]. Her main points are the following.

1. The ability to solve standard quantitative problems does not imply functional understanding. Students must also be able to provide qualitative reasoning, including verbal explanations.

2. Students must participate intellectually in the process of constructing qualitative models that can help them understand relationships and differences among concepts, and develop a functional understanding of the material; otherwise, they tend to accept and use formulae without any sense of appropriateness. Some difficulties are not overcome by traditional instruction, and must be explicitly addressed by multiple challenges in different contexts. Students have spent much of their childhood constructing conceptual models of the world that work very well for them (an object tends to be at rest unless pushed or pulled) and will not accept a different model unless faced with a situation which forces them to discover for themselves that their model is inadequate: what Hewson and

Alan J. Slavin <aslavin@trentu.ca>, Department of Physics, Trent University, Peterborough, ON K9J 7B8

Hewson have called a "conceptual conflict" [7]. McDermott sums this up as "Teaching by telling is an ineffective mode of instruction for most students" [6].

3. The ability to reason scientifically does not usually result from traditional instruction, and must be specifically cultivated.
4. Connections among concepts, physics formulae and the real world are often lacking after traditional instruction. Students must practice interpreting the formalism of physics and relating it to the real world.

A number of different interactive approaches have been developed to address the problems listed above. Here I define *interactive approaches* (IA) to mean those involving structured student-student interactions, whose primary purpose is to develop a conceptual understanding of the material. I am not including the interaction of small groups of students when doing assignments, nor the interaction of a student with a computer *per se*.

The main interactive approaches being used are listed below. Knight provides a full review in *Five Easy Lessons* [8], a book which is also recommended as a resource for addressing common areas of student difficulty in the first-year physics course. A wide range of variations of these methods are in actual use, and the amount of class time devoted to them can vary dramatically. Moreover, several of them can be used to advantage within the same course.

"Peer Instruction" [9] means a Mazur-type approach in which students are assigned the relevant course material to read before class. Lecture time is replaced primarily by small-group discussion of concept-based questions ("ConcepTests"), posed by the instructor, followed by a student vote on multiple-choice answers. If a significant part of the class votes incorrectly, the instructor will discuss the possible answers -- an excellent opportunity to model physical reasoning -- and then ask for student questions. Because the vote was a group decision, students are much more likely to ask questions than if they had voted individually; no one wants to appear dumb in front of her peers, and a collective question reduces this fear. Groups who voted in different ways can be asked to explain their reasoning, but this reduces the amount of material covered. The requirement that students read the material before coming to class and the elimination of formal lecturing permits most of the class time to be spent on the really problematic 20% of the material, where the instructor's expertise is best used. Mazur has used Peer Instruction in classes of some 200 students, but there is no obvious upper limit to its use and there are plans to try it in a class of 1200 at the University of Toronto this year [10].

"Think-pair-share" is similar to Peer Instruction but is usually used in conjunction with more traditional lectures. It is often employed spontaneously at times when the instructor suspects that student understanding is weak. Again, the opportunity to discuss with neighbours encourages student questions.

"Studio physics" replaces formal lectures by lab-based instruction, with an introduction to the material by the instructor being followed immediately by experimental work by the students, usually using computers for data collection and analysis. Students work in pairs or small groups, and follow structured questions in discussing the data and analysis as the lab proceeds.

"Worksheet tutorials" comprise an integrated system of pretests, worksheets, and homework assignments, developed by McDermott's group at the University of Washington [11]. The tutorial session is based on worksheet exercises designed to develop strong conceptual understanding, in small groups guided by a TA who has received prior training with the worksheet.

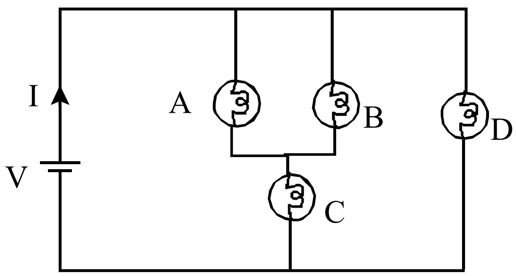
"Interactive demonstrations" [12] function in a manner similar to a Peer Instruction class, but with a demonstration taking the place of the ConcepTest. The instructor first describes the apparatus and how it will be used. The students, working in small groups, then write down their prediction of the outcome, and some of these predictions are presented to the class. The instructor carries out the demonstration and discusses differences between the results and the predictions.

In "Just-in-time teaching" (JITT) [13], students complete a web-based, multiple-choice, graded quiz on the assigned reading material just prior to the class time. It often includes an ungraded text-answer question regarding the part of the reading the student found difficult. JITT spurs students to do assigned readings, and provides the instructor with feedback on student difficulties. Although not normally an interactive technique, JITT is often used in conjunction with Peer Instruction and so has been included here.

The most extensive evaluation of the effectiveness of interactive teaching approaches compared to more traditional ones is that by Hake [14], who compiled the performance of over 6000 American students on the Force Concept Inventory [15] (FCI) test for simple mechanics. The survey included 14 traditional courses and 48 courses making substantial use of interactive methods. The test was taken both at the start of the course, and at the end. The figure of merit used is the normalized gain g, defined as the improvement between the two tests as a percentage of the possible improvement. For example, a student with a score of 60% on the pre-test and 70% on the post-test would have g = 10/40 = 25%. Students in the IA courses had an average g-value of 0.48, almost two standard deviations above the 0.23 for the traditional courses. Tests similar to the FCI are now available for other areas of introductory physics [16].

The interactive teaching approach chosen for the introductory course at Trent University is Peer Instruction, so some examples will be given. Fig. 1 shows a typical ConcepTest, in that it requires only an understanding of basic physics concepts and has embedded in it the potential for students to confront many of the classical misunderstandings: (1) The problem cannot be done unless numerical values for V, I and R are given. (2) Current is "used up" as it travels

Rank the following **identical** bulbs in order of brightness. The brightness of each of these bulbs depends only on the magnitude of the electric current through it, and you can ignore the wiring resistance.



(a) A>B>C>D (b) A>B>C=D (c)A=B>D>C

(d) D>C>A=B (e) C>A=B>D

Fig. 1 Typical ConcepTest for the introductory physics course.

$$d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{d\vec{s}\times\hat{r}}{r^2}$$

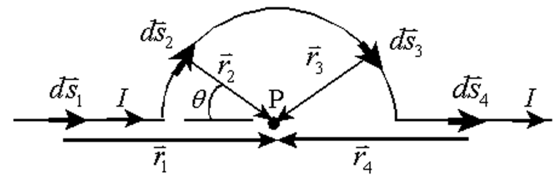


Fig 2 Concept question for determining the magnetic field from a current distribution.

through the wire so C<A=B. (3) The current is weaker the further the lamp is from the source, so D is the least bright and A>B.

Not only can the concept questions be used to develop conceptual understanding, they can also help develop problem-solving skills by working through several stages of a typical problem. An example is shown in Fig. 2, for which the final goal is to use the Biot-Savart law to calculate the magnetic field at point P due to the full current distribution shown. The questions asked are as follows, with the figure repeated on a separate viewgraph for each question, for clarity. Questions 1 and 2 test the understanding of the cross product; question 3 tests the understanding of how the total field is obtained from the integral (sum) of the $d\vec{B}$'s.

1. The magnetic field at P due to the current I in each of current elements $d\vec{s}_1, d\vec{s}_2, d\vec{s}_3, d\vec{s}_4$ is (a) into the page (b) out of the page (c) up (d) down (e) zero.

2. The magnitude of the magnetic field at P due to only the current in $d\vec{s}_2$ is

(a) $dB = \frac{\mu_0 I}{4\pi}\frac{ds\cdot 1\cdot \sin 90^o}{r^2}$ (b) $dB = \frac{\mu_0 I}{4\pi}\frac{ds\cdot r\cdot \cos 90^o}{r^2}$

(c) $dB = \frac{\mu_0 I}{4\pi}\frac{ds\cdot 1\cdot \sin\theta}{r^2}$ (d) $dB = \frac{\mu_0 I}{4\pi}\frac{ds\cdot r\cdot \sin 90^o}{r^2}$

(e) none of the above

3. The total magnetic field at P from the current in the wire is

(a) $B_P = \frac{\mu_0 I}{4\pi}\frac{\pi r^2}{r^2}$ (b) $B_P = \frac{\mu_0 I}{4\pi}\frac{\pi r}{r^2}$ (c) $B_P = \frac{\mu_0 I}{4\pi}\frac{2\pi r}{r^2}$

(d) $B_P = \frac{\mu_0 I}{4\pi}\frac{ds\sin 90^o}{r^2}$ (e) none of the above.

IMPLEMENTATION OF PEER INSTRUCTION AT TRENT UNIVERSITY

Course Context

Student demand for introductory physics at Trent is relatively small, so only one course is provided at this level. The class has about 90 students, divided roughly equally among physics majors, students needing it for health sciences, and those who take it as a minor complement to other programs. The course goals are to provide physics content and conceptual understanding, reasoning and problem-solving ability, and experimental and communication skills. It covers the usual material of a first-year course, with three hours of classroom instruction per week in a lecture hall, plus a fortnightly lab which alternates with a fortnightly tutorial. The lab experiments are coordinated with the classroom theory and are largely traditional.

The course is structured as follows. Pre-class readings introduce the basic ideas and definitions while "lecture" class time uses Peer Instruction to develop conceptual understanding of the concepts. The ungraded tutorial sessions help students apply the concepts to solving problems with a subsequent problem set submitted for grading. The lab serves several purposes: it provides hands-on experience with the concepts discussed in class, and develops experimental, group, and writing skills. In the tutorial sessions the students work in small groups, and concept-based questions are included along with more traditional numerical problems. Early trials of the Think-Pair-Share approach over several years in the Introductory Physics course evolved into Peer Instruction when Mazur's book appeared in 1997. At the time, an implementation of the studio physics approach was not possible because of its cost, and "interactive demonstrations" are incorporated naturally into Peer Instruction.

Use of JITT.

It was quickly apparent that an obstacle with Peer Instruction was the small number of students who did the pre-class readings, as low as 25%. This problem was overcome by the introduction of JITT, implemented through

WebCT [17], a web-based "Class Tools" program that provides for on-line, multiple-choice questioning with instant grading, among other features. By assigning a course grade of 5% for two multiple-choice questions on each pre-class reading, answered on WebCT prior to the class, the number of students doing the readings increased to over 70%. I believe that this represents most of the students who come to class regularly. These two questions focus on material such as definitions, which must be learned but do not require conceptual understanding. A third, ungraded JITT question asks "What part of the reading requires more class discussion?" Prior to class, the instructor scans the text answers to this third question and the WebCT-generated statistics to the multiple-choice questions, and uses these in selecting the choice of ConcepTests for the day. Usually, carefully chosen concept questions satisfy the students' concerns for "more class discussion" of material.

Scheduling Readings

The simplest way to implement Peer Instruction is to begin by developing the pre-class reading schedule for the entire course, with each day's reading covering roughly what would have been covered that day with lecturing. JITT questions are then devised to cover the same material with the same due dates. Making all the JITT questions available at the start of the academic year reduces subsequent work. This lets students organize their JITT quizzes around other commitments, and very few work so far ahead that they forget what they have read. Once a library of concept questions has been developed, they can be selected rapidly based on the material to be covered and the JITT responses. At least for the introductory course, a large number of concept questions is available online [18] or as pdf files on the diskette included with Mazur's book. When these are inadequate, one just develops a new question. An advantage to the use of overhead transparencies is that a blank transparency can be placed on top of the one with the question, and a tally of student responses, clarification of the question, or development of the answer can be done on the blank without marking the original.

Student Buy-In

Most students will be experiencing lectures in their other courses so, as pointed out by Mazur, it is important to tell them -- more than once -- why they are being taught differently; i.e., studies have shown that they will learn better with IA techniques. Most students at this level still believe that there are a limited number of physics "formulae" and problem "types" that they will encounter, and that there is a standard approach to attacking each of them: all they need to do is memorize these. They want the instructor to provide these approaches rather than demanding that they reason from basic principles. Showing them Hake's graph of student performance on the FCI test helps convince them to accept your approach, but one must be careful not to refer to it as the Force Concept Inventory if it is to be used in the course, as it is readily available.

One way to wean students from depending on memorized formulae is to provide them with a sheet at the first of the year, which they also receive at exams, which has only those formulae that they are not expected either to memorize or to be able to derive themselves on an exam. Any calculated answer to assignments must originate either from basic definitions or from a formula on the sheet, or it is downgraded dramatically even if it gives the correct numerical answer. This rapidly reduces the practice of searching the text for the "correct formula", and students usually appreciate the approach by the end of the year even though they can be frustrated after the first assignment, when they need an explanation why just obtaining the correct numerical answer is not the same as "doing physics".

There are always a few students who sit by themselves and so cannot participate in the peer discussions. It is useful to approach these students individually in the first few classes to explain why they should participate and offer to introduce them to another nearby student. Most shy students will accept this offer, but some have genuine phobias of interacting with other people and will insist on being left alone; this desire should be respected.

Instructor's Use of Discussion Time

There are usually one or two groups who have no idea how to begin to answer a given concept question. A valuable use of the instructor's time during the group-discussion periods is to go to such a group and initiate a "Socratic dialogue" in which the instructor asks questions that lead the students to approach the problem constructively. This exchange often provides useful insights for the instructor when she discusses the "correct" approach after the class votes.

Student Voting

Mazur recommends that students vote twice on each concept question, once before discussing the question with his peers, and again after. This forces the student to formulate an individual response first, based on his understanding, and so prepares him for any conceptual conflict that emerges from the group discussion. However, this approach requires that the multiple-choice answers be provided when a problem is first introduced, which limits the degree to which students can develop their own answers. An alternative is not to provide the multiple-choice answers to the students initially, but still ask them to decide on an answer individually before trying to reach a consensus with their colleagues; they then are presented with the multiple-choice answers and asked to vote.

The simplest method for voting is a showing of hands, but has the drawback of biasing the vote: it takes a very confident student in the back half of the class to vote for any answer which is not supported by a large number of students. The second simplest approach is to provide the students with cards labelled A to F in a font large enough to be readable from the front of the classroom. Advantages to the card system are that it is cheap, fast, and shows the instructor when most of the groups are done their discussion. The third common voting method is the use of hand-held electronic devices, available from a number of suppliers [19], which transmit the student's choice to a receiver so voting is anonymous to the students. One advantage to this system is that the instructor can monitor individual student performance or do a statistical analysis of class performance if desired. The transmitters are clearly very useful for someone carrying out research on the Peer Instruction method, but otherwise do not seem to provide a large advantage over the printed cards.

Correlation between Student Performance and Attendance

One study which seems to be absent is a comparison between the test performance of the students who attend the Peer Instruction classes and those who miss classes. It is difficult to believe that test performance would not be highly correlated with attendance, given that the class is where conceptual understanding is specifically addressed, unless Worksheet Tutorials are also used. However, it would be useful to have the statistics to convince dubious students of this, who often claim that their time is better spent studying on their own. For a rough correlation, we have recorded for 22 class days the absence of students who did not pick up their graded assignments or tests in classes in which the assignments were returned. The students who missed more than half of these classes obtained an average final grade only 56% of that for students who missed no classes. Of course, such students were likely delinquent in other components of the course as well, so one would expect their test performance to be poor in any case.

Student Groups

Students usually sit with those of similar academic abilities. This raises the question of whether it is best to allow this to happen, or to put students of varying abilities in the same discussion group. Logistically, the latter may be difficult except in quite small classes, but may not be preferable in any case. Peer pressure is enormous, and a poor student will rarely try to explain his thinking to a strong student in a group situation; the risk of being embarrassed is too great. At the same time, weak students sitting together do discuss the questions, and often take advantage of the instructor's offer for individual assistance during the discussion periods.

Faculty Workload With Peer Instruction

There is substantial start-up time involved with implementing Peer Instruction, though probably not much more than in teaching any course for the first time. Enough concept questions are readily available to form a good starting library, and the initial day-by-day scheduling and writing of the JITT quizzes can be done in about a day. Putting these quizzes into WebCT is quite time-consuming, but it is reasonable to expect the university's instructional development centre to assist in this task. On a daily basis, it takes about a half hour to skim the student replies to the JITT quizzes and select the concept questions, roughly the same time spent previously reviewing lecture notes.

More problematic is the source of the assigned readings. Until very recently, we could not find a text book that was clear enough in its explanation of the concepts to be acceptable, and so we distributed an expanded, word-processed version of my original lecture notes [20] to the students and assigned the readings from them. Creating such notes, especially the drawings and equations, is a very large amount of work that should be avoided if possible. A textbook was still recommended as a backup reference and as the source of assigned problems. However, this situation has changed this year with the publication of R. Knight's textbook [21], which has incorporated much of the education research and is the best text we have seen for providing an understandable introduction for the pre-class readings. However, it does require the students to read about 20 pages for each class meeting, although if they ignore most of the sidebars and worked solutions this reduces the reading by about one half. Three months into the course there have been few complaints about the length of the readings.

Peer Instruction in Upper-Year Courses

A modified Peer Instruction approach has also been used in upper-year classes at Trent in several courses. Again the students are given pre-class reading assignments that cover

Table 1. Student Evaluation of Peer Instruction and JITT in the Introductory Physics Course
The numbers are the student responses in percentages. NR = No Response

a	b	c	d	e	f	NR	Summary (for those responding)
Peer-Instruction							
1. By the end of the course, how did your understanding of the material taught in this format compare with that obtained from a conventional lecture format? (a) Much worse ... (f) Much Better							
3.9	3.9	9.8	17.6	31.4	31.4	2.0	82.0% "Better understanding"
2. How did the work load compare with a class taught in the lecture format? (a) Much more ... (f) Much less							
11.8	11.8	49.0	19.6	3.9	2.0	2.0	74.1% "More work"
3. How enjoyable/interesting did you find the classes compared to a conventional lecture? (a) Much less ... Much more							
2.0	7.8	3.9	23.5	33.3	27.5	2.0	86.0% "More enjoyable"
4. Overall, how do you rank this form of teaching compared to a conventional lecture format? (a) Much worse ... (f) Much better							
2.0	7.8	9.8	13.7	27.5	37.3	2.0	80.1% "Better"
JITT Quizzes							
1. In the process of understanding the course material, WebCT quizzes were (a) Not useful ... (f) Very useful							
0.0	9.8	11.8	27.5	31.4	17.6	2.0	78.1% "Useful"
2. The marking of the WebCT quizzes was (a) Not fair ... (f) Fair							
0.0	0.0	0.0	5.9	17.6	74.5	2.0	100% "Fair"
3. Overall, the use of WebCT in this course was (a) Not helpful ... (f) Very helpful							
3.9	2.0	7.8	9.8	25.5	49.0	2.0	86.0% "Helpful"

Table 2. Interactive Teaching in Canadian Universties

University	Year level	Course material	Interactive methods	% of "lecture"	Contact
Acadia	1	Mechanics, E&M	Studio Physics	60	P. Williams
Alberta	1&2, physics & eng'g	Mechanics, fluids, optics, thermal physics, E&M	On-line discussions with instructor	10-25	I.Y. Isaac
Concordia	1	Mechanics, waves& modern physics	Reflective write-pair-share[a]	60	C. Kalman
	Gen. ed.	Origins of universe	Peer Instruction	100	B. Frank
	1	Mechanics, E&M		15	B. Frank
	1	Waves & modern physics	Reflective/concept writing[a]	50	S. Misra
Guelph	1&2	Mechanics, fluids, elasticity, diffusion, heat transfer	Think-pair-share; interactive demos.	10	E. McFarland
	1&2	Mechanics, waves, E&M, circuits	Think-pair-share; interactive demos; Socratic method.	20	J. O'Meara
	3, 4	statistical & quantum physics, solid state	Socratic method, group activities/ problem solving, Peer Instruction	10	E. Nicol
Lethbridge	1&2	Intro to biophysics, E&M	Peer Instruction	30-50	D. Siminovitch
McGill	1	Mechanics, waves	Peer Instruction.	80	R. Harris
	2	Musical acoustics	Modified PBL[b]	60	R. Harris
	1	E&M	Peer Instruction.	80	M. Knutt
McMaster	1	Mechanics, E&M, waves	Peer Instruction, Interactive tutorials	30	K. Sills
Memorial	1	Statistics, error analysis, mechanics, waves	Studio physics (to be replaced).	100	J. Whitehead
	4	Solid state physics	Peer Instruct., JITT	90	K. Poduska
Mount Allison	1	Mechanics, optics, waves, circuits, E&M, relativity, quantum	Studio physics	100	R. Bruning R. Hawkes D.Hornidge C.Pettipas P. Varma
	3, 4	Waves, mechanics, relativity	Studio physics	65	R. Bruning R. Hawkes
Saskatchewan	1	Mechanics, waves, fluids, optics, E&M.	Peer Instruction , JITT	15	R. Pywell
Toronto	1	Mechanics	Peer Instruction, JITT, Worksheet tutorials.	35	D. Harrison
	1	Mechanics, waves, E&M, relativity, quantum physics.	Peer Instruction		S. Morris
Trent	1	Mechanics, E&M, optics, relativity, quantum .	Peer Instruction, JITT.	90	A. Slavin R.Wortis
	2, 3, 4	Atomic & molecular, electronics, thermal physics, solid state.	Peer Instruction	90	A. Slavin
	1	Physics for elementary school teachers	Modified studio physics[c]	100	J. Earnshaw/ J. Beda

a: "Reflective write-pair-share"[22] at Concordia involves reflective writing by students before class based on readings, conceptual conflict exercises during class (small groups with reports by two groups with different conceptual views followed by class discussion and demos), an individual critique (argumentative essay with different conceptual points of view highlighted assigned for one to two weeks later), and essay questions on the exam and reflective-write-pair-share during class.

b: "Modified PBL" (Problem-based learning[23]) here means that the course is taught using scenarios, chosen by the instructor to relate to the students' interests and experience. They learn by answering structured questions in well-defined groups.

c: This course is designed for prospective elementary-school teachers with little science background and often severe math and science phobias, and is based on the *Powerful Ideas in Physical Science*[24] materials developed by AAPT. As for studio physics there are no lectures, but only a few labs involve computers.

what would have been covered in a lecture, and class time is spent in small-group discussion of the concept-based questions. Some of the questions are amenable to multiple-choice answers and can be addressed by voting, but many require multi-step calculations. As groups work on these questions, the instructor offers individual groups assistance to bridge difficult areas and will occasionally interrupt the class for a short explanation when most of the class is having difficulties with the same concept. One advantage to this approach over traditional lectures is that it exposes unanticipated problem areas. I am unaware of research on the success of Peer Instruction in upper-year courses, perhaps because the typically small class size means that it is not possible to form a control group and there is a significant variation in the class ability from year. However, there is no obvious reason why it should not also be effective here.

The following example of a question in solid-state physics may give a sense of this approach in an upper-year course. The usual textbook development of electron density of states employs the quasi-continuum approximation for electronic energy levels in a solid, which allows the use of calculus. This question forces students to consider the distribution of individual electrons among quantum states and so helps conceptual understanding.

Example: A 2-dimensional free-electron metal has dimensions 1 nm x 1 nm, and contains 80 electrons. (a) Sketch the positions of several allowed states in one quadrant of reciprocal space, under periodic boundary conditions. (b) Show which of these is occupied at T = 0 K. (c) Roughly what is the value of the Fermi energy, in eV? (d) From your sketch in (a), determine approximately the value of the energy density-of-states at the Fermi energy, in eV^{-1}.

Student Response

Table 1 shows the results of a voluntary, on-line, course evaluation carried out for the introductory course at the end of 2003-04. 50 students participated from a class of 80. Student response to the teaching approaches was very positive; the rating of a higher work load than in a lecture-based course partly reflects the nature of physics, as students also rated the work load high when it was lecture-based. Evaluations of Peer Instruction in upper-year courses have been very similar, with a large majority of students preferring it to a lecture approach.

INTERACTIVE TEACHING IN OTHER CANADIAN PHYSICS DEPARTMENTS

A survey has been carried out to determine the extent of interactive teaching methods in other Canadian physics departments, with a letter being sent to all Physics Chairs across Canada asking them to send the questionnaire to relevant faculty. The results are given in Table 2, with the names of the faculty involved. The 5th column gives the approximate percentage of each "lecture" class devoted to the interactive approaches listed. Over 20% of the country's physics departments report using some form of interactive teaching, primarily at the first-year level. Of the 26 instructors listed in the table, 11 are full professors, 4 are contract instructors, and the rest are tenured or tenure-track faculty or permanent teaching staff. This shows a healthy distribution of instructors of all ranks who are exploring new teaching approaches.

SUMMARY

A number of approaches are being used for teaching large classes in a highly interactive manner, including the Peer Instruction technique discussed above. It would be useful to see a study of their effectiveness in upper-year courses. The research into physics pedagogy is having a substantial impact on Canadian university instruction.

ACKNOWLEDGEMENTS

The author gratefully acknowledges many discussions on teaching effectiveness with J. Earnshaw and R. Wortis, and the assistance of Trent's Instructional Development Centre.

REFERENCES

1. A.B. Aarons, *A Guide to Introductory Physics Teaching*, John Wiley and Sons, 1990.
2. S. Billings-Gagliardi, S.V. Barrett, and K.M. Mazor, *Medical Education* **38**, 1061-1070 (2004).
3. http://www.phys.washington.edu/groups/peg/
4. http://galileo.harvard.edu/home.html
5. http://www.physics.umd.edu/perg/
6. L.C. McDermott, in *Conference on the Introductory Physics Course*, p.33-45 (J. Wilson, Editor) John Wiley and Sons, 1997.
7. P. Hewson and M. Hewson, *Instructional Science* **13**, 1-13 (1984).
8. R. D. Knight, *Five Easy Lessons: Strategies for Successful Physics Teaching*, Addison Wesley, 2002.
9. E. Mazur, *Peer Instruction*, Addison Wesley, 1997.
10. D.M. Harrison, University of Toronto, personal communication.
11. L.C. McDermott, Peter S. Shaffer, and the Physics Education Group, *Tutorials in Introductory Physics*, Prentice Hall, 2002 .
12. For example, D.R. Sokoloff and R.K. Thornton, *Interactive Lecture Demonstrations*, John Wiley & Sons, 2004.
13. G. M. Novak, E. T. Patterson, A. D. Gavrin, and W. Christian, *Just-In-Time Teaching*, Addison Wesley, 1999.
14. R. R. Hake, *Am. J. Phys*. **66**, 64-74 (1998).
15. D. Hestenes, M. Welles, and G. Swackhamer, *Phys. Teach*. **30**, 141-158 (1992).
16. http://www.ncsu.edu/per/TestInfo.html
17. WebCT Canada, University of British Columbia, Vancouver; http://www.webct.com.
18. http://galileo.harvard.edu/home.html
19. May be purchased through textbook publishers, or see advertisements in *The Physics Teacher*.
20. Available from A. Slavin, Trent University, as WordPerfect files.
21. R.D. Knight, *Physics for Scientists and Engineers*, Pearson/Addison Wesley, 2004. Another new text which incorporates recent research in physics pedagogy is *Understanding Physics* by K. Cummings, P. Laws, E. Redish and P. Cooney, John Wiley & Sons, 2004.

22 C.S. Kalman, *Academic Exchange Quarterly*,**Winter issue**, 194-198 (2003); Table found at http://rapidintellect.com/AEQweb/2490table.htm; C.S. Kalman, *Science & Education* **11**, 83-94 (2002).

23 T.M. Duffy and D.J. Cunningham, in *Handbook of Research for Educational Research and Technology*, (D.H. Jonassen, Editor), pp. 189-194, MacMillan, 1996.

24 *Powerful Ideas in Physical Science*, American Association of Physics Teachers, 2004.