Introduction

Is teaching an art or a science? This question often initiates discussion in courses for preservice teachers. A serious attempt to answer this question would involve an examination of the evidence for our theories of teaching and learning. To look for scientific rigor, one would check for the control of variables, use of control groups, randomization of test subjects, experimental blinding, reproducibility of results, alternative interpretations of results, and peer review. The relatively new field of physics education research (PER) meets these standards. This is not surprising since PER is mostly conducted by physicists who are inclined to such scientific rigor by training and experience. Furthermore, PER is a growing science. Until recently, the forums for presenting physics education research were limited to more general journals such as *The American Journal of Physics*, *The Physics Teacher*, *Science Education*, *The Journal of Research in Science Teaching*, and *The Journal of College Science Teaching*. Recently, two new peer-reviewed journals have been created specifically for the presentation, discussion, and archiving of PER. In 1999 the American Association of Physics Teachers published the first issue of the *Physics Education Research Supplement to the American Journal of Physics*. In the summer of 2002, the Illinois State University Department of Physics published the first issue of *The Journal of Physics Teacher Education Online*.[1] Yet as the body of PER knowledge continues to grow, no single "correct" method for teaching physics has emerged. In the absence of such a method, the daily act of physics teaching will continue to be an art, but this art should be informed by the science of physics education research.

In the following presentation, I examine some of the results of PER and how these results impinge on the practice of teaching and learning physics. Next, I present some modest experiments in PER which I conducted at Kent State University in the 1999-2000 academic year. Finally, I examine a large-scale attempt to apply the results of PER to the introductory physics program at Kent State University between 2000 and 2002.

Chapter 1: A Background of Physics Education Research

Misconceptions

Since the early 1980's, researchers have discovered that following the completion of an introductory physics course, most of the students hold a variety of misconceptions.[2 3 4 5 6 7 8 9 10 11] In many cases, these are actually preconceptions (ideas held before instruction) which endure through the instruction. In other cases, the students develop the misconceptions during the course. These misconceptions span the introductory physics curriculum, ranging from a misunderstanding of acceleration[2] to confusion regarding the deBroglie wavelength.[3] A few of these misconceptions are well documented, but notwithstanding notable efforts,[4 5 6 12] there exists no widely accepted, comprehensive list of them. In most cases, these misconceptions are not obvious to the instructor and they are highly resistant to change.

As Ibrahim Halloun and David Hestenes observe, these enduring misconceptions present a serious challenge to physics instructors:

> Our diagnostic test results show that a student's initial knowledge has a large effect on his performance in physics, but conventional instruction produces comparatively small improvements in his basic knowledge. The implications of failure on the part of conventional instruction could hardly be more serious, for we are not talking about a few isolated facts that students failed to pick up. One's basic physical knowledge provides the conceptual vocabulary one uses to understand physical phenomena . . . [This] does not mean simply that basic concepts of Newtonian mechanics are missing; it means that alternative misconceptions about mechanics are firmly in place. If such misconceptions are not corrected early in the course, the students will not only fail to understand much of the material, but worse, he is likely to dress up his misconceptions in scientific jargon, giving the false impression that he has learned something about science.[8]

Instruments for Measuring Student Misconceptions

Most of the known misconceptions have been discovered through lengthy interviews with physics students. Since these interviews require an enormous investment of time, several researchers have constructed multiple-choice tests in order to efficiently diagnose specific misconceptions.

The Force Concept Inventory

The first widely used research-based conceptual survey was the Force Concept Inventory (FCI), published in 1992 by David Hestenes, Malcolm Wells, and Gregg Swackhamer.[13] This 30-question multiple-choice survey was designed to identify misconceptions in the understanding of position, velocity, acceleration, and Newton's Laws. In administering the FCI to over 1500 high-school students and over 500 university students, Hestenes *et. al*. found that:

1. The mean pretest score on the FCI (prior to instruction) is 33% (σ = 13%), with mean class scores ranging from 27% to 52%.
2. The mean post test score on the FCI (after instruction) is 58% (σ = 17%), with mean class scores ranging from 48% to 77%.
3. FCI post test performances correlate strongly with performances on the Mechanics Baseline Test,[14] which measures problem-solving ability in elementary mechanics.
4. FCI post test performances do not correlate strongly with teacher competence or the average socioeconomic level of each school.

5. FCI post test performances tend to be weaker when teachers employ traditional teaching strategies, but stronger when teachers employ an inquiry-based strategy.

The Force and Motion Conceptual Evaluation

The Force Concept Inventory has been widely used for ten years. Although this has resulted in a large body of data,[25] some researchers have questioned the validity of the FCI. Specifically, Douglas Huffman and Patricia Heller have shown that individual students often answer FCI items inconsistently with each other.[15] According to Huffman and Heller, a student might demonstrate a correct understanding of Newton's Third Law in one question, a misconception regarding Newton's Third Law in a second question, and a different misconception regarding Newton's Third Law in a third question. Although David Hestenes and Ibrahim Halloun have responded to these concerns in defense of the FCI,[16 17] these questions have motivated (in part) the development of a new test, the Force and Motion Conceptual Evaluation (FMCE), published in 1998 by Ronald Thornton and David Sokoloff.[18] The authors claim that student responses to questions on the FMCE correlate well with each other. At present, many researchers use both the FCI and the FMCE. The FCI is used for the large body of data associated with it; the FMCE is used for its reputation for improved consistency.

Other Conceptual Physics Tests

Other multiple-choice conceptual physics tests include the Mathematical Modeling Conceptual Evaluation,[19] the Test of Understanding Graphs—Kinematics,[20] the Thermal

Concept Evaluation,[21] Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT),[22] and the Conceptual Survey in Electricity and Magnetism (CSEM).[23]

Conventional Instruction

The general characteristics of conventional physics instruction are:

1. Most of the instructional time is spent in teacher-to-student communication, *i. e.* the instructor presents information and the students receive it. As long as a presentation is the dominant instructional mode, the use of technology or demonstrations does not alter the traditional nature of the instruction. During the class period, the instructor may briefly ask or answer questions, but this also does not change the fundamental nature of the instruction.
2. Most of the concepts are presented and/or mathematically derived by the instructor. Although these concepts may be experimentally confirmed in the laboratory, the lecture presentation is considered to be complete, *i. e.* the laboratory experience is not essential to understanding the material.
3. The instructor is rewarded for clarity, entertainment value, and grading "fairly," *i. e.* maintaining a clear dependence of test questions on class presentations and homework.
4. Students believe that understanding is not essential to performing well, as demonstrated by Andrew Elby in a study of 106 introductory college physics students. Using a written questionnaire, Elby investigated the students' epistemological beliefs and performance habits:

My questionnaire focuses on the difference between how physics students study and how they would advise a hypothetical student to study if she were trying to learn physics deeply, with no grade pressure. Students' advice to the hypothetical student reflects their epistemological beliefs about what it means to learn and understand physics. By contrast, their own self-reported study habits reflect a combination of habits, epistemological beliefs, and course-specific beliefs about how to get high grades.

The results indicate that most students perceive learning physics deeply to be a significantly different activity from trying to do well in the course. Specifically, students report spending more time focusing on formulas and practice problems and less time focusing on concepts and real-life examples than they would spend if grades didn't matter.[24]

5. As noted above, conventional instruction has little effect on student preconceptions, and this result seems to be independent of the competence, experience, or popularity of the instructor. [8] [13]

Interactive-Engagement Teaching Techniques

Richard Hake defines "interactive-engagement" teaching techniques as "those designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors."[25] Specifically, interactive-engagement instruction is characterized by guided inquiry, debate, and the opportunity to refine or test ideas.[26]

As noted above, Hestenes, Wells, and Swackhamer found that inquiry-based teaching strategies tended to produce higher FCI scores than conventional teaching strategies.[13] Yet higher post test scores do not necessarily correlate to better instruction. For example, a student who pretests at 20% and post tests at 80% on the FCI learns more than a student who pretests at 60% and post tests at 80%. In order to accurately evaluate conceptual learning, Richard R. Hake defined <g>, the "gain" on the Force Concept Inventory, as "the ratio of the actual average gain (%<post> - %<pre>) to the maximum possible average gain (100 - %<pre>)."[25] Using the "Hake gain" as an evaluative tool, Hake surveyed 14 traditional courses (2, 084 students) and 48 courses employing interactive-engagement methods (4, 458 students). He found that:

1. Regardless of the experience, competence, or popularity of the instructor, traditional instruction never produced an average <g> of greater than 30% on the FCI. For traditional instruction, the average <g> for all instructors was 23% ($\sigma = 4\%$).[27]
2. Interactive-engagement methods produced <g> scores of up to 70%. For interactive-engagement methods, the average <g> was 48% ($\sigma = 14\%$).[27]

As measured by the Hake gain on the FCI, students in interactive-engagement courses learned more of the conceptual base of mechanics. Since Hestenes *et al.* demonstrated that FCI scores correlate strongly with problem-solving ability, Hake's research supports the general conclusion that interactive-engagement methods are superior to conventional physics instruction in both conceptual understanding and problem-solving ability. Further research indicates that the conceptual gains are relatively permanent, *i. e.* years after completing interactive-engagement instruction, students continue to score well on the FCI.[28] Other research indicates that completion of an interactive-engagement introductory physics course correlates to success in subsequent traditional physics classes.[29]

Examples of Interactive-Engagement Instruction

Socratic Dialogue

In conventional instruction, the primary role of the instructor is to give information and answer questions. In many interactive-engagement teaching methods, the primary role of the instructor is to guide the students by asking questions. Of course, this teaching technique is very old, and its most famous practitioner is Plato's Socrates. Richard Hake gives the following example of Socratic guidance in an introductory physics laboratory at Indiana University. As part of an exercise, the students were asked to carry a wooden disk across the room at a constant velocity. They are debating the question, "Is there a horizontal force acting on the disk."

Student 1:	Our table can't agree on this but I think I have it right.
Socrates:	*Why did you put a horizontal force vector on your sketches?*
Student 1:	Because the disk is moving. If it's moving it's gotta have a force on it.
Socrates:	*How is the disk moving?*
Student 2:	Because we pushed on it.
Socrates:	*Can you describe the motion?*
Student 2:	Like it says: "in a straight line at a constant speed."
Socrates:	*Did it feel as if you were exerting a horizontal force?*
Student 2:	Not much—I walked pretty slow.
Student 1:	So did I.
Socrates:	*Why, then, did you both draw horizontal force vectors as large as the vertical force vectors?*
Student 1:	I guess that's wrong. Maybe it should be a tenth as big.
Student 2:	I'd say more like a fifth.
Student 1:	Anyway, it's pretty tiny . . . but it's gotta be there, otherwise it wouldn't move.
Student 2:	Yeah, that's right.
Socrates:	*How fast did you walk?*
Student 2:	Pretty slow . . . um . . . umm . . . maybe . . . uhh . . . 5 miles an hour.
Socrates:	*So if you moved at 500 miles an hour?*
Student 2:	Oh yeah . . . we'd feel it then!

Socrates: *Feel what?*
Student 2: The horizontal force on the disk.
Socrates: *You mean $F_{on\ disk\ by\ hand}$?*
Student 2: Hmm . . . um . . . um . . . Oh yeah . . .
Student 1: Well . . . ah . . . What *we'd* feel is the reaction $F_{\text{on hand by disk}}$.
Student 2: . . . Yep . . . That's it.
Socrates; *GOOD! Have you flown in an airplane?*
Student 1: Yeah . . . Pretty fast . . . um . . . maybe 500 miles an hour.
Socrates: *What does Newton's First Law say about that? Think about this and I'll return later if you still need some assistance.*[30]

In this dialogue, the subject matter is noteworthy. A typical physics instructor might view Newton's First Law as an easily-learned concept which would warrant scant attention. Here, the students and instructor are spending considerable time on it because these students may be able to recite Newton's First Law, but they probably do not understand it and they certainly do not believe it. Although declarative statements may eventually be necessary for floundering students, the instructor avoids such statements in this case because these could end the students' thought process. Furthermore, the instructor's questions are skillfully balanced. As Arnold Arons observes:

> The problem is to provide students with enough Socratic guidance to lead them into the thinking and forming of insights but not so much as to give everything away and thus destroy the attendant intellectual experience.[31]

Arons lists questions such as "How do we know . . ." and "What is the evidence for . . ." as essential to a Socratic interview. Finally, note that the instructor does not resort to technical language. Arons cautions that the instructor must be wary of students who can accurately use technical jargon without understanding the ideas behind the terms:

> In my own courses, I indicate from the first day that we will operate under the precept "idea first and name afterwards" and that scientific terms acquire meaning only through the description of shared experience in words of prior definition. When students try to exhibit erudition (or take refuge from questioning) by name dropping technical terms that have not yet been defined, I and my staff go completely blank and uncomprehending. Students catch on to this game quite quickly. They cease name dropping and begin to recognize, on their own, when they do not understand the meaning of a term.[32]

Studio Physics

In the dialogue cited above, the students initiated the discussion. When they reached an impasse, they brought the instructor into the discussion. The "Studio Physics" model utilizes such student-to-student dialogue as the primary teaching tool for the course. Whereas Hake and Arons used laboratory-based Socratic dialogue to supplement a traditional large lecture-style physics course, the "Studio Physics" model bases the entire course on laboratory-based inquiry.

Developed at the University of Washington, Lillian C. McDermott's pioneering *Physics by Inquiry*[33] workbooks are aimed at preservice teachers. As they follow the workbook instructions, the students perform laboratory exercises and answer questions in small groups. At certain points in each unit, the workbooks instruct the students to stop and check their reasoning with a staff member. Using Socratic questioning techniques, the instructor checks for and extends student understanding. Following the course, preservice elementary teachers routinely outperform calculus-based physics students in answering conceptual questions and solving conceptual problems.[34] McDermott and the University of Washington Physics Education Group has also developed *Tutorials in Introductory Physics*,[35] intended for use in the recitation sections of (otherwise) traditional calculus-based introductory physics courses, but they have not developed an entire algebra- or calculus-based introductory studio course.

In addition to a rigorous testing and refinement program,[36 37 38] the McDermott materials are notable for their reliance on relatively inexpensive, easily obtained equipment. By contrast, the microcomputer is an essential tool in all of the other studio physics programs. At Dickinson College, Priscilla W. Laws' *Workshop Physics*[39] forms the basis of the entire calculus-based introductory physics sequence. At Rensselaer Polytechnic Institute, Jack Wilson and others have developed the Comprehensive Unified Physics Learning Environment (CUPLE), a microcomputer-based studio course.[40 41] Studio physics is also used at the Colorado School of Mines[42] and North Carolina State University.[52] On the high-school level, the NSF-sponsored Constructing Physics Understanding program (CPU) has trained many teachers in a computer-intensive studio method.[43]

Modeling

The "modeling" program is rooted in a specific epistemology which holds that the creation and manipulation of mental models are fundamental to human knowledge and understanding.[44 45] Student preconceptions are believed to be rooted in incorrect models which must be dismantled and replaced with correct models. Based on experiment and discussion, this is achieved through selecting and/or constructing a model, validating the model, analyzing the model (including the development of a mathematical structure), and deploying the model in new situations.[46 47] At this point, the "modeling" program has been developed as an award-winning[48] high school studio program,[49] but a university counterpart is under development.[50] However, preliminary research indicates that the high school materials and methods are effective in algebra-based physics courses on the university level.[51]

Large Classes

All of the interactive-engagement teaching methods described so far are implemented in classes of no more than 50 students. At North Carolina State University, efforts are underway to implement the studio model on a much larger scale.[52] [53] Others have developed altogether different interactive-engagement techniques for use in a large classroom. The most widely used technique is Eric Mazur's *Peer Instruction*.[54] In Mazur's technique, the detailed lectures typical of large classes are replaced by several presentations of approximately 10 minutes each. These lectures exclude the details, so the students are required to read the textbook for the historical development of the ideas and to learn many of the problem-solving techniques. Following each presentation, the instructor poses a "ConcepTest,"[55] *i. e.* a conceptual question. One of Mazur's questions is

> A car accelerates from rest. In doing so the absolute value of the car's momentum changes by a certain amount and that of the earth changes by
>
> 1. a larger amount.
> 2. the same amount.
> 3. a smaller amount.
> 4. The answer depends on the interaction between the two.[56]

The presentation of the ConcepTest initiates the peer instruction sequence:

1.	Question posed	1 minute
2.	Students given time to think	1 minute
3.	Students record individual answers (optional)	
4.	Students convince their neighbors (peer instruction)	1-2 minutes
5.	Students record revised answers (optional)	
6.	Feedback to teacher: Tally of answers	
7.	Explanation of correct answer	2+ minutes[57]

The keys to Mazur's method are the debate between students and the feedback to the teacher, usually by a class-wide vote on the correct answer. In these moments, the students confront and adjust their preconceptions.

Building on the peer instruction format, David Sokoloff and Ronald Thornton have developed "Interactive Lecture Demonstrations (ILD's),"[58] [59] in which the ConcepTests are replaced by demonstrations. Instead of answering a multiple-choice question, each student predicts the outcome of a demonstration in writing, discusses it with her neighbors, and votes on the outcome. After each student has voted, the instructor conducts the demonstration and a discussion of the result.

Chapter 2: Original Physics Education Research

Testing the Test: Questions About the Force Concept Inventory

1. Does the prestest influence post test performance?

When a student takes the FCI pretest, her incorrect answers are based on her preconceptions. When she takes the post test, she may have correctly learned the Newtonian world view, but she may also remember her answers from the pretest. Consequently, one might hypothesize that the pretest negatively influences her performance on the post test.

In order to test this hypothesis, I pretested and post tested a small calculus-based first-semester introductory physics class at Kent State University in the fall of 1999. The control group of 5 students took the FCI as a pretest.[60] The experimental group of 8 students took a placebo pretest, the "Math Inventory Test." (See Appendix A.) Since the FCI consists of 30 questions of five choices each, I designed the "Math Inventory Test" in parallel format, also consisting of 30 questions of five choices each. On the day of the pretest, the professor walked along each row of students, alternately handing each student an FCI or a Math Inventory. No students were informed of the nature of the experiment. The results appear in Table 1, Experiment 1. Note that originally 34 students were pretested, but because of course attrition and absences on the day of the post test, only 13 students were post tested. Since the FCI post test average for the experimental group (58% ± 9%) is not significantly different from the post test average for the control group (48% ± 10%), these results do not indicate that the pretest influences post test performance.

Table 1: Experiments Examining the Force Concept Inventory

Experiment	**Number of Students**	**FCI Pretest** (%)	**σ** (%)	**FCI Post Test** (%)	**σ** (%)	**Gain <g>** (%)	**σ** (%)
1 control	5	38 ± 9	18	48 ± 10	20	17 ± 9	17
1 exp.	8	- - - - -	- -	58 ± 9	22	- - - - -	- -
2	45	35 ± 3	15	45 ± 3	18	14 ± 4	20
3 control	42	29 ± 2	11	49 ± 3	15	28 ± 4	21
3 exp.	34	22 ± 2	11	46 ± 3	13	31 ± 4	17
4 control	20	53 ± 4	15	71 ± 5	19	44 ± 7	30
4 exp.	18	56 ± 4	15	78 ± 4	15	53 ± 8	30

2. Do large FCI gains result from instructional method or increased exposure to conceptual material?

An instructor who chooses interactive-engagement methods is consciously attempting to improve conceptual understanding. Normally this results in a greater time investment in conceptual questions and a smaller time investment in mathematical derivations, problem solving, or other activities characteristic of conventional instruction. One might attribute the improved conceptual understanding to the increased exposure to conceptual material rather than the instructional method. What if conventionally instructed students were required to answer conceptual questions? In this case, high FCI gains would indicate that exposure to conceptual material is primarily responsible for the greater conceptual understanding.

In the spring of 2000, I experimented on an algebra-based introductory physics class at Kent State University. I asked the instructor to use the same conventional teaching methods that he had used in past courses. Since the instructor felt that any difference in treatment of the students could be interpreted as an unjust advantage of one group over another, I did not separate the students into experimental and control groups. According to Hake, no conventional instructor had produced FCI gains which exceeded 30%.[25] If these students crossed the 30% threshold, I would take this as evidence that exposure to conceptual material was a significant factor.

I assembled a set of 93 multiple-choice conceptual questions to be added to the students' regular homework throughout the semester. About one third of these questions were taken directly from Mazur's database of ConcepTests;[55 61] the rest follow Mazur's format. (See Appendix B.) The normal homework load was not reduced, so the addition of the conceptual questions increased the total homework load of the students. Normally, the responsibility for presenting homework solutions falls to the recitation instructor, a graduate teaching assistant who meets with the students for 50 minutes per week. Consequently, the recitation instructor bore the primary responsibility for explaining the answers to the conceptual questions, although the classroom instructor occasionally answered these questions at student request.

The results appear in Table 1, Experiment 2. Since the 14% gain is less than the average FCI gain for conventional instruction reported by Hake,[25] I conclude that in this experiment, the increased exposure to conceptual material resulted in no increase in conceptual understanding. This supports Hake's conclusion that the interactive-engagement teaching techniques are primarily responsible for improving conceptual understanding.

3. Do student gains improve when students identify which of Newton's Laws apply?

Although a student may learn and understand Newton's Laws, his successful performance on the FCI depends on his "activation" of the relevant concepts in the context of each question. One might hypothesize that if a student records which of Newton's Laws (I, II, or III) he is invoking when he answers a question, he might be less likely to revert to his nonNewtonian preconceptions.

In the 1999-2000 academic year, I pretested a total of 76 students in four of my introductory high school physics classes. Just before post testing, I rolled a die to assign two of the classes (42 students) to the control group and the other two classes (34 students) to the experimental group. The control group simply took the FCI post test. The experimental group took the FCI, but I instructed them to write a I, II, or III next to each question to designate whether they were invoking Newton's first, second, or third law in answering each question. I also instructed them that where appropriate, they could choose more than one of Newton's laws.

Consulting Table I, Experiment 3, I find no significant difference between the experimental and control groups. I conclude that in this study, identifying which of Newton's Laws apply to each question had no significant influence on FCI gains.

4. Do gains improve when the students write an explanation to each item on the FCI?

It is possible that a student understands Newton's Laws, but does not take the time to complete a Newtonian analysis of each item on the FCI. If an explanation of each item is required, the student may "activate" the Newtonian concepts when answering the questions.

In the 1999-2000 school year, I taught both of the A. P. Physics classes at Copley High School, totaling 38 students. For both the pretest and the post test, I used the take-home test system normally used in these classes, in which each student takes home a sealed test, unseals it in the presence of a parent or guardian who serves as proctor, takes the test, and finally seals it in a fresh envelope. All 38 students used this procedure to take the FCI pretest. In the post test, the control group used the same procedure as the pretest. However, when the members of the experimental group unsealed their tests, they found an FCI and a paper with 30 numbered spaces of three lines each. These students were instructed to write an explanation for each of their answers on the FCI. In order to randomize the students, I alternated the two types of sealed tests in a stack, then the students were invited to take them as they left the classroom. The students did not know that the procedures were not the same for everyone until after the tests were returned. (Afterward, one of the experimental students expressed annoyance that she had to work harder than the control students.) Also, I did not know who was control or experimental until receiving the completed tests.

The results appear in Table I, Experiment 4. Since the 9% difference in gain falls within the range of the standard error, I cannot conclude that gains improve when the students write an explanation for each item on the FCI. However, this result warrants further study.

Introducing Interactive-Engagement Methods to the Algebra-Based Physics I Laboratory at Kent State University

Summer 2000

In the summer of 2000, we modified the first semester of Kent State University's algebra-based introductory physics course. No changes were made in the lecture or recitation portions of the course, *i. e.* they followed conventional instructional methods. However, I modified six of the thirteen laboratory experiences as follows:

1. Most of the six labs began with an introductory ConcepTest, intended to prepare the students for the lab.
2. Wherever possible, the students were encouraged to design their own experiments rather than follow a rigid procedure.
3. The students answered a series of post-lab conceptual questions. These questions were intended to improve student reflection over the laboratory results.
4. In two of the experiments, the students employed electronic accelerometers.

The results appear in Table 2. These relatively modest changes increased the mean FCI gain from 14% (spring 2000) to 32% (summer 2000). Encouraged by this result, I conducted a more extensive modification of the lab in the summer of 2001.

Table 2: Interactive-Engagement in the Algebra-Based Physics I Lab

Semester	**Number of Students**	**Pretest** (%)	**σ** (%)	**Post Test** (%)	**σ** (%)	**Gain <g>** (%)	**σ** (%)
Spring 2000 FCI	45	35 ± 3	15	45 ± 3	18	14 ± 4	20
Summer 2000 FCI	30	27 ± 3	13	51 ± 3	13	32 ± 3	16
Summer 2001 FCI	45	33 ± 2	13	56 ± 3	18	36 ± 4	22
Summer 2001 FMCE	45	21 ± 2	14	42 ± 4	22	28 ± 6	25

Summer 2001

In the summer of 2001, I extensively modified the first-semester algebra-based physics lab:

1. I replaced the standard lab manual with conceptually-oriented lab sheets. (see Appendix C.)
2. I introduced computers, Vernier LabPro interfaces, and probes. In some experiments, the students used the computers and probes to collect data; in other experiments, the students used the computer to graph and analyze the data.
3. Each lab period began with a graded quiz over previous material.
4. In order to prevent any students from settling into the role of passive lab partner, I rotated lab partners every week. I maintained a deck of index cards with the students' names on them. At the beginning of each lab session, I shuffled and dealt the cards to determine lab partners for the day.

5. Each lab began with a demonstration of the equipment to be used. In a guided class discussion, the students identified relevant variables and prioritized them. Next, the students chose variables for study and identified independent vs. dependent variables in a variety of situations. Finally, the students chose, designed, and conducted experiments.
6. As each group completed the experiment, I checked the results. When I was satisfied with the experimental procedures and data analysis, I gave them a set of questions to discuss and answer. In order to encourage intellectual exploration, neither the lab results nor the lab questions were graded for accuracy.
7. Near the end of the period, I discussed lab questions as well as previous homework and quizzes. Since the homework and quizzes were based on the lab session, these were graded for accuracy.

The results appear in Table 2. Surprisingly, these extensive modifications produced approximately the same FCI gain (36%) as the modest changes in the previous summer (32%). The FMCE gain (28%) is comparable to the FCI gain. Also, these gains are lower than the 48% average gain reported by Hake[25] for interactive-engagement methods.

Introducing Interactive-Engagement Methods to the Physics II Laboratory at Kent State University

Establishing a Baseline for Semester II Topics, Spring 2001

In the spring of 2001, I used the Conceptual Survey of Electricity and Magnetism (CSEM) to test a second-semester calculus-based introductory physics class at KSU. Consulting Table 3, the gain is a disappointing 7%. By comparison, the authors of the CSEM found a mean gain of 26% for all classes. [23] At present, there is no published data correlating CSEM gains to teaching methods.

An Interactive-Engagement Physics II Lab, Summer 2002

In the summer of 2002, I modified the second-semester algebra-based physics lab:

1. I assembled a set of conceptually-oriented lab sheets. (See Appendix D.) Unlike the first-semester effort, these sheets prescribe step-by-step procedures, thereby eliminating the prelab demonstration, discussion of variables, and student choice of experimental procedure which characterized the first-semester effort.
2. The other features of the first-semester effort were retained, including the use of computers and probes, conceptual quizzes, rotating lab partners, conceptual lab questions, and the end-of-period discussion.

The results appear in Table 3. The 27% CSEM gain represents a considerable improvement over the spring 2001 result.

Table 3: Interactive-Engagement in the Physics II Lab

Semester	**Number of Students**	**Pretest (%)**	**σ (%)**	**Post Test (%)**	**σ (%)**	**Gain <g> (%)**	**σ (%)**
Spring 2001 CSEM (Calculus-Based)	15	23 ± 2	6	29 ± 3	9	7 ± 4	14
Summer 2002 CSEM (Algebra-Based)	35	24 ± 2	10	45 ± 3	13	27 ± 3	18
Summer 2002 DIRECT (Algebra-Based)	35	27 ± 2	8	47 ± 2	12	27 ± 3	17
Fall 2002 CSEM (Algebra-Based)	32	25 ± 2	7	35 ± 2	12	13 ± 3	13
Fall 2002 DIRECT (Algebra-Based)	32	26 ± 2	10	37 ± 3	12	14 ± 4	18
Fall 2002 CSEM (Calculus-Based)	13	28 ± 3	8	48 ± 5	14	29 ± 5	17
Fall 2002 DIRECT (Calculus-Based)	13	28 ± 3	8	47 ± 5	15	27 ± 6	18

Graduate Teaching Assistants, Fall 2002

In fall 2002, the summer 2002 curriculum (Appendix D) was adopted in both the algebra-based and calculus-based second-semester courses, but I did not directly teach the lab. Instead, I met with the teaching assistants (graduate students in physics) once each week in order to explore the equipment and explain the curriculum.

The results appear in Table 3. In the algebra-based course, both the CSEM and DIRECT gains are significantly lower than the gains in the previous summer. I attribute this lower gain to two problems:

1. The instructors did not always understand the grading procedures. In particular, the homework and quizzes were to be graded based on accuracy, but the lab sheets and lab questions were not. More than half way into the semester, I learned that the algebra-based instructors were grading the lab sheets and lab

questions for accuracy. Supported by Elby's study,[24] I hypothesize that this added grade pressure probably caused the students to focus on "getting the correct answers" rather than intellectual exploration.

2. As the semester progressed, I gradually realized that some of the teaching assistants in the algebra-based courses held misconceptions.

In contrast to the gains in the algebra-based course, the DIRECT and CSEM gains in the calculus-based course are approximately the same as the gains from the previous summer. These instructors followed the established grading procedures and appeared to have a stronger conceptual understanding. Furthermore, these labs met for three hours rather than two hours and a professor regularly supplemented the lab materials with mini-lectures and questions.

Discussion and Conclusions

These results are encouraging. Although the lab represents only 1/3 of the instructional time, FCI gains rose from 14% to 36% in the first-semester course and CSEM gains rose from 7% to 27% in the second-semester course. However, the FCI gains are lower than the 48% mean for interactive-engagement instruction reported by Hake. In order to build on these improvements, I recommend:

1. Rewrite the materials to improve the interactive-engagement nature of the activities. In particular, the materials and methods could encourage more student-to-student dialogue and student-to-instructor dialogue.
2. In the fall of 2002, I conducted a relatively modest training program for the graduate teaching assistants. This program could be expanded to improve

the instructors' grasp of the material as well as provide training and practice in interactive-engagement pedagogy.

3. Undergraduate student instructors could be hired. These students would have recently completed the introductory physics program and be good communicators. They would be included in the training program for graduate teaching assistants. Because of their relatively recent experience in the course, the undergraduate teaching assistants will tend to be aware of the conceptual difficulties confronting the students, and their presence would greatly improve the student-to-teacher ratio at a minimal cost.

The laboratory should make a contribution to conceptual understanding, but it should serve other functions as well. Students should learn to control variables, devise experiments, competently analyze data, draw conclusions, and defend these conclusions. If the laboratory is the sole vehicle of conceptual instruction, these other functions may be compromised. Consequently, the entire introductory program should be examined. Because of its smaller enrollments, the calculus-based program could be converted to a studio format. In the algebra-based program, peer instruction could be introduced into the lectures. In the recitation periods, a program such as *Tutorials in Introductory Physics*[35] could be adopted. In any case, a comprehensive, long-term review of the introductory physics courses is warranted.

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