Mini-Course on Physics Education Research and Research-Based Innovations in Physics Instruction

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Supported by the U.S. National Science Foundation, Division of Undergraduate Education, and Division of Research, Evaluation, and Communication

I. Physics Education Research: Laying the Basis for Improved Physics Instruction

Over the past 20 years, systematic investigations have helped to clarify the dynamics of students' thinking during the process of learning physics. This research has revealed students' learning difficulties, as well as aiding in the development of more effective instructional strategies. I will describe the principal goals and methods of Physics Education Research, and discuss some of the methodological issues related to this work. With examples drawn from investigations we have carried out at Iowa State University, I will illustrate this research process and show how it can lead to improved curricula and instructional methods.

Within the past 20 years, physicists have begun to treat the teaching and learning of physics as a research problem. This includes (1) systematic observation and data collection, and carrying out of reproducible experiments, (2) identification and control of variables, and (3) in-depth probing and analysis of students' thinking. This field of study has come to be known as "Physics Education Research" (PER). Broadly speaking, the goals of PER are to improve the effectiveness and efficiency of physics instruction. This is carried out primarily by developing and assessing instructional methods and materials that address obstacles which impede students' learning of physics. The methods of PER include the development and testing of diagnostic instruments that assess student understanding, and the utilization of these instruments to investigate student learning. Students' thinking is probed through analysis of written and verbal explanations of their reasoning, supplemented by multiple-choice diagnostics. Learning is assessed through measures derived from pre- and post-instruction testing.

It is important to realize that there are certain things PER can *not* do: PER can not determine an instructor's "philosophical" approach toward education, such as whether one should focus on improving the achievement of the majority of enrolled students, or instead focus on a subgroup, such as high-ability or low-ability students. PER can not specify the goals of instruction in particular learning environments, such as the appropriate balance between learning of "concepts," and development of mathematical problem-solving skills. PER may help instructors make informed choices about these goals, but it can not determine what they should be.

There are now more than 60 PER groups in U.S. physics departments, including more than 30 in Ph.D.-granting departments. The primary activities of PER groups include (1) research into student learning, (2) research-based curriculum development, (3) assessment of instructional methods, and (4) preparation of K-12 physics and science teachers. Curriculum development is directed both at introductory and advanced courses, lab- and non-lab courses, and courses for teacher preparation. There are many different research themes, including investigations of students' conceptual understanding, development and assessment of diagnostic instruments, students' attitudes and beliefs about learning physics, and many others.

Among the specific issues addressed by PER are these: many (if not most) students (1) develop weak qualitative understanding of physics concepts after standard introductory courses, and (2) lack a "functional" understanding of concepts that would allow them to solve problems in unfamiliar contexts. There are many reasons for this. For one, students hold (or develop during instruction) many firm ideas about the physical world that may conflict with physicists' views. (Examples: an object in motion must be experiencing a force; a given battery always produces the same current in any electric circuit.) Beyond that, most introductory students need a great deal of guidance in developing scientific reasoning skills and using abstract concepts. Most of these students lack "active-learning" skills that would permit more efficient mastery of physics concepts.

One of the ways that PER researchers address these problems is through research-based curriculum development. This involves investigation of student learning with standard instruction, with a focus on probing learning difficulties encountered by students during this instruction. Based on this research, new curricular materials are developed, tested, and modified. Student understanding is assessed to determine whether the new materials actually result in improved learning. I will discuss a simple example of how this process is carried out by outlining some of the work done at Iowa State University to investigate student learning of concepts in gravitation. I will also briefly sketch out another project related to student learning of thermodynamics, and in my next presentation I will describe that project in detail.

In addressing the issues involved in curriculum development, it is useful to remember that at least *some* students learn efficiently. Highly successful physics students are "active learners": they continuously probe their own understanding by posing their own questions, scrutinizing implicit assumptions, examining varied contexts, etc. By contrast, most introductory students are unable to do efficient active learning on their own. They don't know "what questions they need to ask," and they require considerable assistance by instructors using appropriate curricular materials.

To help students become active learners, several principles can be used as a guide: (1) students are led to engage in deeply thought-provoking activities during class time ["interactive engagement"]; (2) students' preexisting "alternative conceptions" and other common learning difficulties are recognized and deliberately elicited; (3) the process of science (exploration and discovery) is used as a means for learning science; students are not necessarily "told" things are true; instead, they are prodded to figure them out for themselves as much as possible ("inquiry-based" learning). The term "Interactive Engagement" [originated by R. Hake] usually implies very high levels of interaction between students and instructor, collaborative group work among students during class time, and intensive active participation by students in learning activities during class time.

Some strategies used to elicit students' preconceptions and learning difficulties include: (1) having students make predictions of the outcome of experiments; (2) requiring students to give written explanations of their reasoning; and (3) posing specific problems that are known to consistently trigger certain learning difficulties. Incorporating inquiry-based learning can be done by giving students an opportunity to investigate or think about concepts before the instructor actually discusses the concept in detail. This may be done either by leading students to draw conclusions based on evidence they acquire in the instructional laboratory, or – in lecture courses – by guiding students through chains of reasoning using printed worksheets. Research-based instruction emphasizes qualitative, non-numerical questions to reduce students' unthinking reliance on algebraic "plug-and-chug." Extensive use is made of multiple representations (graphs, diagrams, computer simulations, verbal descriptions, etc.) and diverse physical contexts in order to deepen students' understanding. Requiring students to explain their reasoning (verbally or in writing) helps them to more clearly expose their thought processes.

I will describe some of the research that has been done on improving students' problem-solving abilities, and I will outline some instructional strategies that have been developed based on that research (e.g., use of multiple representations by Alan Van Heuvelen, and "Context-Rich Problems" by Pat and Ken Heller). I will also outline some instructional strategies using active-learning laboratories ("Workshop Physics" by Laws *et al.*; "Socratic-Dialogue-Inducing Labs" by R. Hake), and active-learning textbooks (*Matter and Interactions* by Chabay and Sherwood; *Understanding Basic Mechanics* by Reif; *Physics: A Strategic Approach* by Knight). Perhaps the oldest and most thoroughly tested instructional approach is that developed at the University of Washington by Lillian C. McDermott and her co-workers. Their method (sometimes known as "Elicit, Confront, Resolve") has led to the development of the widely used research-based curricular materials *Physics by Inquiry* and *Tutorials in Introductory Physics*. Implementing active-learning instructional strategies in large lecture classes is a particular challenge; I will discuss that subject in detail during my third presentation.

Finally, I will discuss some methodological issues involved in PER. A key question for teachers is how to assess the effectiveness of instruction. A single exam measures only a students' instantaneous knowledge state, but instructors are interested in *learning*, i.e., the transition between states. For that, one needs a measure of learning gain that has maximum dependence on instruction, and minimum dependence on students' pre-instruction state. A widely used measure that addresses these needs is Hakes' "normalized gain" or *g*, defined as the learning gain (pre-instruction to post-instruction), divided by the maximum possible gain. I will discuss some of the properties of normalized gain, and some of the issues that are involved in making use of it.

II. Developing Improved Curricula and Instructional Methods based on Physics Education Research

In many research-based curricula, physics students are guided to work their way through carefully designed and tested sequences of questions, exercises, and/or laboratory activities. Utilizing these materials, and interacting frequently during class with instructors and with each other, students have often achieved significant gains in understanding when compared with instruction based on lecture alone. In this presentation I will describe in some detail the process of developing these research-based curricula, as carried out by our group at Iowa State over the past several years. I will show how our research into students' reasoning in thermodynamics is helping guide the development of improved curricular materials. Similarly, investigations of the pedagogical role played by diverse representational modes (mathematical, verbal, diagrammatic, etc.) are also helping us lay the basis for developing more effective instructional methods.

In this presentation I will describe in considerable detail some of the investigations we have carried out regarding student learning of specific topics in physics, and how we have begun to use the results of that research to develop improved instructional materials.

In collaboration with Prof. Tom Greenbowe of the Iowa State Chemistry Education Research Group, we initiated a project to develop improved curricular materials for teaching thermodynamics. To lay the basis for that work, we carried out extensive investigations of student learning in courses using standard instruction. Here I'll discuss an investigation of reasoning regarding heat, work, and the first law of thermodynamics among students in an introductory calculus-based general physics course. We found that responses to written questions by 653 students in three separate courses were very consistent with results of detailed individual interviews carried out with 32 students in a fourth course. Although most students seemed to acquire a reasonable grasp of the state-function concept, it was found that there was a widespread and persistent tendency to improperly over-generalize this concept to apply to both work and heat. A large majority of interviewed students thought that net work done and/or net heat absorbed by a system undergoing a cyclic process must be zero, while only 20% or fewer were able to make effective use of the first law of thermodynamics even after instruction was completed. Students' difficulties seemed to stem in part from the fact that heat, work, and internal energy all share the same units. Results were consistent with those of previously published studies of students in U.S. and European universities, but portray a pervasiveness of confusion regarding process-dependent quantities that was previously unreported. The implication is that significant enhancements of current standard instruction may be required for students to master basic thermodynamic concepts.

Loverude, Kautz, and Heron (University of Washington) have pointed out that a crucial first step to improving student learning of thermodynamics concepts lies in solidifying the student's understanding of the concept of work in the more familiar context of mechanics, with particular attention to the distinction between positive and negative work [*Am. J. Phys*. **70**, 137 (2002)]. Beyond that first step, it seems clear that little progress can be made without first guiding the student to a clear understanding (1) that work in the thermodynamic sense can alter the internal energy of a system, and (2) that "heat" or "heat transfer" in the context of thermodynamics refers to a *change* in some system's internal energy, or equivalently that it represents a quantity of energy that is being *transported* from one system to another.

I will describe some of our initial efforts to develop improved curricular materials and instructional methods for these topics. We are planning to extend this work to more advanced topics, including student learning of statistical physics.

In a related investigation we have explored students' approaches to solving calorimetry problems involving two substances with differing specific heats. We found that students often employ various context-dependent rules-of-thumb such as "*equal energy transfer implies equal temperature change*," and "*temperature changes are directly proportional to specific heat*." Through interviews we found that students frequently get confused by, or tend to overlook, the detailed proportional reasoning or algebraic procedures that could lead to correct solutions. Instead, they often proceed with semi-intuitive reasoning that at times may be productive, but more often leads to inconsistencies and non-uniform conceptual understanding. We have developed new curricular materials that are designed to address these and related learning difficulties. I will illustrate and discuss some of these materials, and describe some of the preliminary testing we have carried out.

Another project done in collaboration with Tom Greenbowe is an investigation of the role played by diverse representational modes in the learning of physics and chemistry. There are two major phases of this work: (1) Probe students' reasoning with widely used representations, such as free-body diagrams, *P-V* diagrams, vector diagrams of various types, etc., and (2) compare student reasoning with different forms of representation of the same concept (verbal, diagrammatic, mathematical, graphical, etc.). In an initial phase of this work with graduate student Ngoc-Loan Nguyen, we investigated the understanding of vector concepts in graphical form among students enrolled in general physics courses at Iowa State University. We found a number of significant learning difficulties related to addition of vectors and ability to manipulate vectors without a coordinate system or grid. Many students had an imprecise understanding of vector direction and a vague notion of vector addition.

In further investigations, we compared students' ability to solve similar (or identical) problems when presented using different forms of representation. We used a "multi-representation quiz" in which a single problem is presented in several different versions, utilizing either words only ("verbal" version), mathematical symbols, graphs, or diagrams. We found significant differences in student performance on some questions, in particular verbal and diagrammatic questions involving Newton's third law. The proportion of students making errors when responding to the diagrammatic version of the questions was consistently higher than in the case of the verbal version. Moreover, many students had difficulty in translating certain phrases such as "exerted on" or "exerted by" into vector-diagram form, and this led to other discrepancies between responses in the two cases. We also found some preliminary evidence that there might be differences between the performance of males and females on electrical circuit-diagram questions: the error rate for females was about 50% greater than that of males, even after identical instruction.

III. Research-Based Active-Learning Instructional Methods in Large-Enrollment Physics Classes

A long-standing challenge has been to incorporate active-learning instructional methods in large-enrollment physics classes traditionally taught in a lecture format. I will describe the methods we have introduced to develop a "fully interactive physics lecture," and discuss the curricular materials that we have created to support this form of instruction. This involves both carefully designed sequences of multiple-choice conceptual questions, and free-response worksheets designed to be used by students working in collaborative groups.

SEE SLIDES BEGINNING NEXT PAGE

Research-Based Active-Learning Instructional Methods in Large-Enrollment Physics Classes

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Supported by NSF DUE #0243258 and DUE #0311450

Research in physics education and other scientific and technical fields suggests that:

- “Teaching by telling” has only limited effectiveness
  - can inform students of isolated bits of factual knowledge
- For understanding of
  - inter-relationships of diverse phenomena
  - deep theoretical explanation of concepts

→ students have to “figure it out for themselves” by struggling intensely with ideas

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Research in physics education and other scientific and technical fields suggests that:

- “Teaching by telling” has only limited effectiveness
  - listening and note-taking have relatively little impact
- Problem-solving activities with rapid feedback yield improved learning gains
  - student group work
  - frequent question-and-answer exchanges with instructor

Goal: Guide students to “figure things out for themselves” as much as possible

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What Role for Instructors?

- Introductory students often don’t know what questions they need to ask
  - or what lines of thinking may be most productive
- Instructor’s role becomes that of guiding students to ask and answer useful questions

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What needs to go on in class?

- Clear and organized presentation by instructor is not *at all* sufficient
- Must find ways to guide students to synthesize concepts in their own minds
- Instructor’s role becomes that of guiding students to ask and answer useful questions
  - aid students to work their way through complex chains of thought

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Keystones of Innovative Pedagogy

- problem-solving activities during class time
- deliberately elicit and address common learning difficulties
- guide students to “figure things out for themselves” as much as possible

The Biggest Challenge: Large Lecture Classes

- Very difficult to sustain active learning in large classroom environments
- Two-way communication between students and instructor becomes paramount obstacle
- Curriculum development must be matched to innovative instructional methods

Active Learning in Large Physics Classes

- **De-emphasis of lecturing**; Instead, ask students to respond to many questions.
- Use of classroom communication systems to obtain **instantaneous feedback** from entire class.
- Cooperative **group work** using carefully structured free-response worksheets

***Goal:** Transform large-class learning environment into "office" learning environment (i.e., instructor + one or two students)*

"Fully Interactive" Physics Lecture

DEM and K. Manivannan, Am. J. Phys. ***70,*** *639 (2002)*

- Very high levels of student-student and student-instructor interaction
- Simulate one-on-one dialogue of instructor's office
- Use numerous structured question sequences, focused on specific concept: small conceptual "step size"
- Use student response system to obtain instantaneous responses from all students simultaneously (e.g., "flash cards")

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Sequence of Activities

- Very brief introductory lectures (≈10 minutes)
- Students work through sequence of multiple-choice questions, signal responses using flash cards
- Some "lecture" time used for group work on worksheets
- Recitations run as "tutorials": students use worksheets with instructor guidance
- Homework assigned out of workbook

Features of the Interactive Lecture

- High frequency of questioning
- Must often create unscripted questions
- Easy questions used to maintain flow
- Many question variants are possible
- Instructor must be prepared to use diverse questioning strategies

Video (18 minutes)

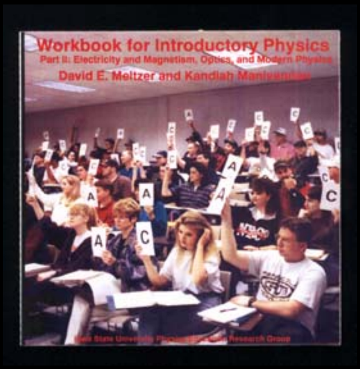
- Excerpt from class taught at Southeastern Louisiana University in 1997
- Algebra-based general physics course
- *First Part:* Students respond to questions written on blackboard.
- *Second Part:* Students respond to questions printed in their workbook.

Curriculum Requirements for Fully Interactive Lecture

- Many question sequences employing multiple representations, covering full range of topics
- Free-response worksheets adaptable for use in lecture hall
- Text reference (“Lecture Notes”) with strong focus on conceptual and qualitative questions

➡ *Workbook for Introductory Physics (DEM and K. Manivannan, CD-ROM, 2002)*

Supported by NSF under
“Assessment of Student Achievement” program



Workbook for Introductory Physics
Part II: Electricity and Magnetism, Optics, and Modern Physics
David E. Meltzer and Kandiah Manivannan
Iowa State University Physics Education Research Group

Curriculum Development on the Fast Track

- Need curricular materials for complete course ⇒ must create, test, and revise “on the fly”
- Daily feedback through in-class use aids assessment
- Pre- and post-testing with standardized diagnostics helps monitor progress

Curricular Material for Large Classes

“Workbook for Introductory Physics”

- Multiple-choice “Flash-Card” Questions
  - Conceptual questions for whole-class interaction
- Worksheets for Student Group Work
  - Sequenced sets of questions requiring written explanations
- Lecture Notes
  - Expository text for reference
- Quizzes and Exams
  - some with worked-out solutions

High frequency of questioning

- Time per question can be as little as 15 seconds, as much as several minutes.
  - similar to rhythm of one-on-one tutoring
- Maintain small conceptual “step size” between questions for high-precision feedback on student understanding.

Must often create unscripted questions

- Not possible to pre-determine all possible discussion paths
- Knowledge of probable conceptual sticking points is important
- Make use of standard question variants
- Write question and answer options on board *(but can delay writing answers, give time for thought)*

Easy questions used to maintain flow

- Easy questions (> 90% correct responses) build confidence and encourage student participation.
- If discussion bogs down due to confusion, can jump start with easier questions.
- Goal is to maintain continuous and productive discussion with and among students.

Many question variants are possible

- Minor alterations to question can generate provocative change in context.
  - add/subtract/change system elements (force, resistance, etc.)
- Use standard questioning paradigms:
  - greater than, less than, equal to
  - increase, decrease, remain the same
  - left, right, up, down, in, out

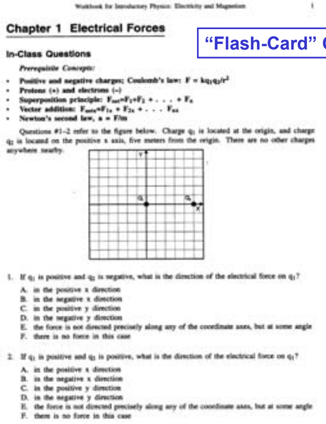
Instructor must be prepared to use diverse questioning strategies

- If discussion dead-ends due to student confusion, might need to backtrack to material already covered.
- If one questioning sequence is not successful, an alternate sequence may be helpful.
- Instructor can solicit suggested answers from students and build discussion on those.

Interactive Question Sequence

- Set of closely related questions addressing diverse aspects of single concept
- Progression from easy to hard questions
- Use multiple representations (diagrams, words, equations, graphs, etc.)
- Emphasis on qualitative, not quantitative questions, to reduce “equation-matching” behavior and promote deeper thinking

“Flash-Card” Questions



Workbook for Introductory Physics: Electricity and Magnetism 1

Chapter 1 Electrical Forces

In-Class Questions

Prerequisite Concepts:

- **Positive and negative charges; Coulomb's law: $F = kq_1q_2/r^2$**
- **Protons (+) and electrons (−)**
- **Superposition principle: $F_{net}=F_1+F_2+\ldots+F_n$**
- **Vector addition: $F_{netx}=F_{1x}+F_{2x}+\ldots F_{nx}$**
- **Newton's second law, $a = F/m$**

Questions #1–2 refer to the figure below. Charge q_1 is located at the origin, and charge q_2 is located on the positive x axis, five meters from the origin. There are no other charges anywhere nearby.

1. If q_1 is positive and q_2 is negative, what is the direction of the electrical force on q_1?
   A. in the positive x direction
   B. in the negative x direction
   C. in the positive y direction
   D. in the negative y direction
   E. the force is not directed precisely along any of the coordinate axes, but at some angle
   F. there is no force in this case

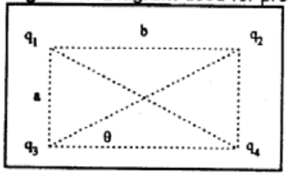
2. If q_1 is positive and q_2 is positive, what is the direction of the electrical force on q_1?
   A. in the positive x direction
   B. in the negative x direction
   C. in the positive y direction
   D. in the negative y direction
   E. the force is not directed precisely along any of the coordinate axes, but at some angle
   F. there is no force in this case

Problem “Dissection” Technique

- Decompose complicated problem into conceptual elements
- Work through problem step by step, with continual feedback from and interaction with the students
- May be applied to both qualitative and quantitative problems

Example: Electrostatic Forces

Figure 1. Diagram used for problem dissection

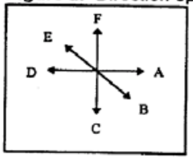


Four charges are arranged on a rectangle as shown in Fig. 1. ($q_1 = q_3 = +10.0$ μC and $q_2 = q_4 = -15.0$ μC; a = 30 cm and b = 40 cm.) Find the magnitude and direction of the resultant electrostatic force on q_1.

Question #1: How many forces (due to electrical interactions) are acting on charge q_1?

(A) 0 (B) 1 (C) 2 (D) 3 (E) 4 (F) Not sure/don’t know

Figure 2. Direction options



For questions #2-4 refer to Fig. 2 and pick a direction from the choices A, B, C, D, E, and F.

Question #2: Direction of force on q_1 due to q_2

Question #3: Direction of force on q_1 due to q_3

Question #4: Direction of force on q_1 due to q_4

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score	<g>
National sample (algebra-based)	402	**27%**	**43%**	**0.22**
National sample (calculus-based)	1496	**37%**	**51%**	**0.22**
ISU 1998	70	**30%**	**75%**	**0.64**
ISU 1999	87	**26%**	**79%**	**0.71**
ISU 2000	66	**29%**	**79%**	**0.70**

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	Mean Score
Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 112: F98 **Six final exam questions**	*76*	77%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	78%

Summary

- Focus on ***what the students are doing in class,*** not on what the instructor is doing
- Guide students to answer questions and solve problems during class
- Maximize interaction between students and instructor ***(use communication system)*** and among students themselves ***(use group work)***