Formative Assessment Materials for Large-Enrollment Physics Lecture Classes

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Synopsis: Real-time In-class Formative Assessment

How can an instructor assess students' thinking during class and modify in-class learning activities accordingly? Finding ways to address this question is the objective of our project. Our goal is to develop and test materials that provide a basis for in-class instructional activities, and which also assist the instructor in monitoring student thinking on a moment-to-moment basis.

Overview

The materials we have developed consist of carefully sequenced sets of multiple-choice items that emphasize qualitative, conceptual questions. (See Fig. 1 for a sample.) They are designed to maximize student-instructor interaction and allow rapid assessment of student learning in a large-class environment. This assessment then aids instructors in structuring and guiding their presentations and class activities

The design of the materials is based on the assumption that the solution of even very simple physics problems invariably hinges on a lengthy chain of concepts and reasoning. Our question sequences guide the student to lay bare these chains of reasoning, and to construct in-depth understanding of physical concepts by step-by-step engagement with conceptual sticking points. Carefully linked sequences of activities first lead the student to confront the conceptual difficulties, and then to resolve them. This strategy is based on one developed at the University of Washington over the past 30 years (1-4). Complex physical problems are broken down into conceptual elements, allowing students to grapple with each one in turn and then return to synthesize a unifying perspective (5).

Over several years the materials have undergone a continuous (and unending) process of testing and revision in actual classroom situations. Constant in-class use reveals ambiguous and confusing wording which is then rapidly corrected in new versions of the materials. Analysis of assessment data provides additional guidance for revision.

Motivation

(*NB*: Here and below, only selected, representative references to the physics education research literature are given. Relevant references to other and earlier work are provided in the Appendix.)

Research in physics education suggests that instructional methods that incorporate in-class problem-solving activities with rapid feedback can yield improved learning gains, in comparison to traditional lecture methods (5, 6). A key to the success of these methods is that instructional activities should elicit and address common conceptual difficulties, difficulties that are often uncovered or probed through in-depth research on student understanding (1-4). When students grapple with conceptual issues by thinking about and solving qualitative problems—problems in which straightforward algebraic procedures may be insufficient (or inefficient) solution methods—learning and retention has often been observed to improve. Instructional methods that engage students in problem-solving activities are sometimes called “active-learning” methods. A particular genre of active-learning methods used in physics has often been referred to by the term “interactive engagement” (6).

Interactive Engagement

Traditionally, instructors (and textbooks) have tended to focus on presenting clearly, precisely, and in painstaking detail the concepts and techniques they wish their students to learn. The emphasis is on the thoroughness and clarity of the presentation (4). However, in recent decades, research into student learning of physics and other technical subjects has demonstrated that for each new concept or technique to be learned, there will often be a number of conceptual “sticking points” for the student (4, 7). Moreover, there has been increasing recognition of the important role of students’ prior (i.e., pre-instruction) knowledge in generating these sticking points and in providing a basis for their eventual resolution (1-4, 8). In addition, more attention has been paid both to the ways in which students’ ideas are linked and organized, and to the nature of students’ approaches to applying their knowledge and to solving problems (5). These realizations have led to a revised view of the instructor’s role.

In this revised view, the central function of the instructor is to direct the focus of class activities and discussion toward the key sticking points in the students’ thought process, and toward specific weaknesses in the organization of students’ knowledge. One has to illuminate in a stark and glaring light, so to speak, the phases in the student’s thought process where a key concept or organizational link may be lacking, so that in the student’s own mind the gap to be filled is clearly sensed, and the eventual synthesis of the concept or link becomes *dramatically* apparent.

Since ideally one must determine where a student stands conceptually—in the process of understanding a particular idea—in order to guide them to the next phase, some form of back-and-forth interchange with them is essential, even in very large classes. The main focus of instruction is first, to identify the ways in which students are putting the idea together in their own minds, so as to pinpoint any errors or gaps that may exist; second, to identify elements of students’ thinking that can potentially form useful and productive components of an improved understanding; third, to allow the students to grapple with a question, example, or problem that requires them to fill out and perfect their understanding. This could be a problem on which they may all work for several minutes, or instead something as simple as the question: “What is the next step here?” The essential point is to ensure their *active* mental participation as thoroughly as is feasible.

The crux of the instructional problem is that students' minds are not blank slates, and they do not absorb concepts simply by being told (*or* shown) that they are true. They must be guided continually to challenge their present state of understanding, and to resolve conceptual confusion through a process of active engagement (1). This may occur either by predicting and then personally investigating the outcome of real physical processes in the instructional laboratory, or by a step-by-step confrontation with conceptual sticking points in the context of a theoretical example (3). Promoting student interaction through the use of cooperative groups can aid this process by having students challenge each others' understanding, and by encouraging them to help each other deepen their comprehension of the subject matter. As any teacher knows, articulating one's thoughts helps improve one's own learning.

These considerations regarding student learning have led to the development and implementation of a variety of instructional methods which, in the context of physics instruction, have often come to be called by the general term "interactive engagement" (6). It is particularly challenging to specify what is meant by this term, in part because it generally refers not simply to specific behaviors by the instructors and the students, but also to specific aspects of the *content* of the instructional materials and activities. These aspects of content refer to features that are explicitly based on consideration of students' pre-instruction knowledge and of their typical learning behaviors. Research has suggested that instruction which incorporates certain useful *behaviors* without also utilizing appropriate *content* may fall far short of the outcomes that result from an appropriate combination of these two key elements (9-11).

In view of these considerations, I will outline some of the prominent features of interactive-engagement instruction in physics. Interactive-engagement instruction generally refers to:

[1] instruction that is informed and guided by knowledge of students' pre-instruction knowledge state (1-4, 12-14), as well as of their learning trajectory (15, 16). This refers to both their pre-existing ideas and to their learning tendencies. These tendencies constitute the ways in which students typically attempt to apply their pre-existing understanding and reasoning processes to issues that emerge during the course of instruction. These include in particular:

   a. specific student learning difficulties related to particular physics concepts (1-4, 6, 8, 12, 14, 17);

   b. specific student ideas and knowledge elements that are productive and useful in helping them grapple with new physics concepts (18);

   c. students' *beliefs* about what they need to do in order to learn (14, 19);

   d. students' actual *behaviors* in the context of the learning process (20).

[2] instruction that guides students to elicit (14) and address specific difficulties typically encountered when studying new concepts, whether by relatively direct methods (in which students are guided to "confront" these difficulties [1-4]) or less direct methods (in which students are guided to "refine" their ideas to "reconcile" them to physics concepts [18]). Other terms that have been applied to this process include "bridging" (21) (i.e., between more familiar and less familiar

concepts) and "weaving" (22) (i.e., of loosely connected initial ideas into more complete understanding).

[3] instruction that emphasizes having students "figure things out for themselves" (13) to the extent that is practical and appropriate. This implies that students are guided to reason out concepts and key ideas through a questioning and discussion process ("guided inquiry"), in contrast to receiving these ideas fully and clearly developed in advance of their problem-solving activity (1-4, 13, 23). In the initial stages, instructors tend to ask students many questions rather than provide either direct answers or detailed formulations of generalized principles. Carefully structured question sequences are often used in this process (3). (Detailed formulations of general principles may however be appropriate at a later stage of the process.)

[4] instruction that emphasizes having students engage in a wide variety of problem-solving activities during class time, in contrast to spending most of the time listening to an instructor speak (6, 8).

[5] instruction that leads students to express their reasoning explicitly both in verbal form by interacting with instructors and other students, and in written form through explanations written as part of responses to quiz, homework, and exam problems (1-4, 13, 14, 22-26). This helps students more clearly expose—and therefore modify—their own thought processes.

[6] instruction that incorporates students working together in small groups in which they are led both to express their own thinking, and to comment on and critique each others' thinking regarding problems and questions posed for their consideration (3, 4, 14, 17, 26).

[7] instruction that ensures that students receive rapid feedback in the course of their problem-solving activity (5, 6) (rapid in the sense of a minute-to-minute time scale). This includes feedback from instructors through frequent questions and answers, and feedback from fellow students through small-group interaction.

[8] instruction that emphasizes qualitative reasoning and conceptual thinking (1-4, 5, 13, 14, 23-25). Non-quantitative means of problem solving are used to strengthen students' understanding of fundamental ideas, and to avoid having students focus on mastery of mathematical algorithms as a substitute for that understanding.

[9] instruction that seeks to deepen conceptual understanding by posing problems and eliciting solutions in a wide variety of contexts and representations, incorporating diagrammatic, graphical, pictorial, verbal, and other means of representing ideas and resolving questions (2, 4, 5, 14, 17, 22-31).

Note that this list emphasizes the *content* of instructional materials and activities (particularly in items #1, 2, 8, and 9) as much as it does the specific instructional *behaviors* (such as those in items #3-7). It has become clear that in order to fulfill the objectives of this form of instruction, substantial prior investigation of students' thinking and learning behaviors is required. This type of research lays the basis for, in particular, the first two items in the process outlined above. Instruction that is based on physics education research of this type is often called "research-based" instruction. Instruction that, by contrast, employs some of the same learning behaviors but in which the content does *not* focus on areas identified with specific learning difficulties is not, apparently, as successful.

Several investigations have addressed the issue of ostensibly "interactive," yet not-very-effective learning environments within the context of physics education. A common theme is that such less-effective environments are missing a key element by not addressing students' *actual* learning difficulties. (Such difficulties may be uncovered through research.) In a study by Redish, Saul and Steinberg (9), even lectures "with much student interaction and discussion" had little impact on student learning. Hake discusses and analyzes courses supposedly based on interactive engagement that produced subpar learning results (6). In her Ph.D. research, Pam Kraus (10) looked at this issue more systematically. After a lengthy investigation, she arrived at the following conclusion:

> *In many of our efforts to improve student understanding of important concepts, we have been able to create an environment in which students are mentally engaged during the lecture. While we have found this to be a necessary condition for an instructional intervention to be successful, it has not proved sufficient. Of equal importance is the nature of the specific questions and situations that students are asked to think about and discuss.* [Ref. 10, p. 286]

Kraus specifies the key criteria she found effective in improving instruction: *eliciting* students' preconceptions with carefully designed questions, guiding them to *confront* these ideas through appropriate discussion and debate involving all the students, and leading students to *resolve* their difficulties with well-chosen alternative models. A somewhat different alternative approach that has been reported as successful is to guide students to generate and then test their own explanations for patterns observed in simple experiments (28).

In a careful study reported by Cummings et al. (11), "studio" instruction which involved students working together in small groups using computers was compared with research-based instruction in a similar environment. They found that although the studio-physics classrooms appeared to be interactive and students seemed to be engaged in their own learning, learning outcomes were the same as with traditional instruction. By contrast, introduction of research-based techniques and activities generated significant gains in conceptual understanding, although the studio-classroom environment was otherwise the same as before.

Interactive Engagement in the context of large classes

A number of workers in recent years have explicitly addressed the challenge of the large-class learning environment in the context of physics. Van Heuvelen (29, 32), developed free-response worksheets for use by students during class meetings in the lecture hall. Eric Mazur (33, 34) has achieved great success in popularizing "Peer Instruction," the method he developed for suspending a lecture at regular intervals with challenging conceptual questions posed to the whole class. Students discuss the questions with each other and offer responses using a classroom communication system. Sokoloff and Thornton (35) have adapted microcomputer-based laboratory materials for use in large lecture classes, in the form of “Interactive Lecture Demonstrations.” Novak and collaborators (36) have developed “Just-In Time Teaching,” which makes use of pre-class web-based computer warm-up exercises, and in-class group work by students using whiteboards. To some extent these incorporate similar methods used and promoted by Hake (13, 17), and also by Hestenes and his collaborators (30). The Physics Education Group at the University of Washington has experimented with modifications of their “Tutorials in Introductory Physics” (37), adapted for use in large lecture classes (10). Other implementations of active learning in large physics classes using classroom communication systems have been described by the group at the University of Massachusetts, Amherst (38), Poulis et al. (39), Shapiro (40), Burnstein and Lederman (41), Lenaerts et al. (42), and Reay et al. (43), as well as others. The “Scale-Up” project at North Carolina State University (44) also makes use of technology-based systems with similar goals in mind.

It is worth emphasizing that extensive empirical evidence of the instructional effectiveness of these various techniques has been published both in the references cited, and in many other sources cited in turn by those references. To choose just one illustrative example, the effectiveness of the *elicit-confront-resolve* method as implemented in the “Tutorials” developed at the University of Washington (3, 37) has been demonstrated repeatedly by multiple investigators at a variety of institutions, including the use of longitudinal studies, with very consistent results (45). Learning gains generated through use of these materials were clearly superior to those achieved with more traditional instruction. In view of this vast array of direct empirical evidence, the recent finding of only a “weakly positive” relationship between science achievement and loosely defined “reformed-oriented practices” (46) must be taken to reflect limitations either of that particular study, or of the specific instructional practices probed by that investigation.

Current Project: Formative assessment materials for fully interactive lectures

The specific methods we employ and the materials we have developed are, in effect, a variant of Peer Instruction as developed by Mazur. The basic strategy is to drastically increase the quantity and quality of *interaction* that occurs in class between the instructor and the students, and among the students themselves. To this end, the instructor poses many questions. All of the students must decide on an answer to the question, discuss their ideas with each other, and provide their responses to the instructor using a classroom communication system. The instructor makes immediate use of these responses by tailoring the succeeding questions and discussion to most effectively match the students’ pace of understanding.

In an office or small-group environment, the instructor is relatively easily able to get an ongoing sense of where the students are “conceptually,” and how well they are following the ideas that are being presented. By getting continual feedback from them, the instructor is able to tailor his or her presentation to the students’ actual pace of understanding. The methods we use allow one, to a large extent, to transform the environment of the lecture hall into that of a small seminar room in which all the students are actively engaged in the discussion.

Our methods begin with a de-emphasis of lecturing. Instead, students are asked to respond to questions targeted at known learning difficulties. We use a classroom communication system to obtain instantaneous feedback from the entire class, and we incorporate group work using both multiple-choice and free-response items. We refer to this method as the “fully interactive lecture” and have described it in detail elsewhere (47). In the remainder of this section I give a brief synopsis of this method. (*Note:* Since this particular project was restricted to creation of the multiple-choice items, I will not further discuss the free-response items in this paper.)

We ask questions during class and solicit student responses using printed flashcards (containing letters A, B, C, D, E, and F) or with an electronic “clicker” system. The questions stress qualitative concepts involving comparison of magnitudes (e.g., “*Which is larger: A, B, or C?”*), directions (*“Which way will it move?”*) and trends (*“Will it decrease, remain the same, or increase?”*). These kinds of questions are hard to answer by plugging numbers into an equation.

We give the students some time to consider their response, 15 seconds to several minutes depending on the difficulty. Then we ask them to signal their response by holding up one of the cards, everybody at once. Immediately, we can tell whether most of the students have the answer we were seeking—or if, instead, there is a “split vote,” half with one answer, half with another. If there is a split vote, we ask them to talk to each other. Eventually, if necessary, we will step in to—we hope—alleviate the confusion. If they haven’t already figured things out by themselves, they will now at least be in an excellent position to make sense out of any argument we offer to them.

The time allotted per question varies, leading to a rhythm similar to that of one-on-one tutoring. The questions emphasize qualitative reasoning, to reduce “equation-matching” behavior and to promote deeper thinking. Questions in a sequence progress from relatively simple to more challenging. They are closely linked to each other to explore just one or two concepts from a multitude of perspectives, using a variety of representations such as diagrams, graphs, pictures, words, and equations. We maintain a small conceptual “step size” between questions for high-precision feedback on student understanding; this allows more precise fine tuning of the class discussion. In line with this objective, we employ a large proportion of “easy” questions, that is, questions to which more than 80% of students respond correctly.

We find that easy questions build confidence, encourage student participation, and are important signals to the instructor of students’ current knowledge baseline. Often enough, questions thought by the instructor to be simple turn out not to be, requiring some backtracking. Because of that inherent degree of unpredictability, some proportion of the questions asked will turn out to be quite easy for the students. If the discussion bogs down due to confusion, it can be jump-started with easier questions. The goal is to maintain a continuous and productive discussion with and among the students.

Many question variants are possible. Almost any physics problem may be turned into an appropriate conceptual question. By using the basic question paradigms "increase, decrease, remain the same," "greater than, less than, equal to," and "left, right, up, down, in, out," along with obvious variations, it is possible to rapidly create many questions that probe students' qualitative thinking about a system. By introducing minor alterations in a physical system (adding a force, increasing a resistance, etc.), students can be guided to apply their conceptual understanding in a variety of contexts. In this way, the instructor is able to provide a vivid model of the flexible and adaptive mental approach needed for active learning.

The development and validation of the question sequences is the central task of this project. Many question sequences are needed to cover the full range of topics in the physics course curriculum. (Other materials needed for interactive lecture instruction include free-response worksheets and text reference materials, but these are under development as part of separate projects.)

Results of Assessment

In earlier projects related to this one, we have carried out extensive assessment of student learning. We found that learning gains on qualitative problems were well above national norms for students in traditional courses, at the same time that performance on quantitative problems was comparable to (or slightly better than) that of students in traditional courses (47). These findings are typical of other research-based instructional methods (4, 8).

Validation check and collection of baseline data

Up until recently, the process of drafting our assessment items has been based on extensive instructional experience, knowledge of the results of physics education research (48), and experience in the use of previous, related assessment items. As part of the present project, we have begun to include a more systematic validation process to help confirm that the items both test the knowledge they are intended to test, and catalyze students' reasoning process in the manner intended. This validation process employs patient and time-consuming "think-aloud" interviews with individual students, recorded digitally or on audiotape (49). This particular project has focused on using these interviews for development of the multiple-choice question sequences, although in other work we have used such interview techniques very extensively as part of the development of free-response materials (50).

In this type of process, students are asked to work through the sequence of questions, explaining their reasoning as they go, while the interviewer examines the details of the student's thinking with gently probing questions. This process can be very effective in (a) uncovering confusing or ambiguous language and word usage; (b) confirming that the students interpret the meaning of the question in the manner intended; and (c) determining whether the students make any tacit assumptions intended by the question (e.g., no external electric field), and do not impose any unintended assumptions (e.g., a need to consider very weak forces). The outcome of this process is to substantially strengthen the quality and utility of the collection of assessment items as a whole. Our data from this phase of the project are as yet only preliminary, but we hope to significantly expand this aspect of the work in the future.

One of the goals of this project was to record student responses to each of the assessment items, including those items already developed and class-tested, as well as the items that were developed as a result of the present project. These response data will provide a baseline benchmark for comparison when other instructors make use of the assessment materials, and will assist other instructors in planning and interpreting the use of the materials. Samples of these data (obtained at Iowa State University) are shown in Fig. 1. They illustrate that correct-response rates on the first few questions in a given sequence are relatively high (80% or greater); as the sequence progresses to more challenging items, response rates can drop to the 50-70% level or less. It is these more challenging questions that usually generate the most productive discussions.

As part of previous projects, initial versions of question sequences for topics in electricity and magnetism, optics, and modern physics had been created. During the present project, we have worked on additional materials for magnetism and modern physics, as well as materials for selected topics in mechanics. Ultimately, we intend to complete question sequences for the full two-semester introductory physics course.

Conclusion

Although the methods described here have focused on physics instruction, it is clear that they have broad potential applicability to a wide variety of technical fields. As may be verified in part by consulting the rapidly expanding list of citations (51) to Crouch and Mazur's paper on Peer Instruction (34), similar methods have been embraced and found useful by, among others, astronomers, geoscientists, physiologists, chemists, engineers, and computer scientists.

Acknowledgments

Thomas J. Greenbowe assumed responsibilities as Principal Investigator for this project upon the author's move to the University of Washington.

Much of the preliminary work on this project was carried out by Ngoc Loan P. Nguyen, a former graduate student at Iowa State University. Mr. Nguyen died unexpectedly in November 2005 as a result of a sudden illness. This was a devastating loss both personally for this author and for the ongoing work of this project, the completion of which is now significantly delayed.

This work has been supported in part by NSF DUE-0243258, DUE-0311450, PHY-0406724, and PHY-0604703.

Appendix: Historical Perspective

Although it is not the purpose of this paper to provide comprehensive references regarding the origins and development of the learning methods cited above, it is useful and interesting to offer some historical perspective. The interactive-engagement teaching methods embraced by researchers in physics education are the products of a long chain of developments. These developments are traceable most directly to educational innovations that followed World War II, although they are partially inspired by still earlier work.

The Physical Science Study Committee project initiated in 1956 by MIT physicists Jerrold Zacharias and Francis Friedman was one of the first steps in this process (52). Eventually involving a broad array of world-famous physicists, this project resulted in a dramatic rethinking of the high-school physics curriculum and generated a new textbook (53) along with ancillary curricular materials. The new curriculum was distinguished by a greatly increased emphasis—in contrast to traditional curricula—on communicating a deep conceptual understanding of the broad themes of physical principles. It represented a rejection of traditional efforts that had relied heavily on memorization of terse formulations and “cookbook”-style instructional laboratories.

Further catalyzed by the launch of Sputnik in 1957 and with strong funding support by the National Science Foundation (NSF), similar curriculum development efforts were initiated by chemists (in 1957), biologists (in 1959), mathematicians (also in 1959, although preliminary efforts had started in 1952), and earth scientists (in 1962) (54). A joint conference sponsored in 1959 by the National Academy of Sciences brought the scientists together with prominent psychologists and educators such as Harvard’s Jerome Bruner and Piaget collaborator Bärbel Inhelder (55). General pedagogical principles that emerged from these discussions were enunciated by Bruner (56), Joseph Schwab (57), and others. Soon, the reform effort expanded to include the elementary schools and, backed by the NSF, an explosion of more than a dozen new science curricula aimed at younger students was generated (58). Prominent physicists again played a central role in several of these curriculum reform projects, notably including Cornell’s Philip Morrison (in the “Elementary Science Study” project [59]) and Berkeley’s Robert Karplus (a key leader in the “Science Curriculum Improvement Study” [60]). Beginning in the late 1960s and early 1970s, these instructional methods were put into action at the university level by the Washington group led by Arnold Arons (61) and Lillian McDermott (62, 63). In these early efforts, Arons and McDermott put great emphasis on the need for students to formulate and express reasoned responses in written or verbal form to questions that they themselves raised during instruction. Initially, these efforts focused on improving the preparation of prospective K-12 science teachers.

Prominent in all of these efforts was a strong emphasis on learning through guided inquiry (sometimes called “discovery”), utilizing the investigational process of science as a means of teaching scientific concepts themselves (57). In this process, students would be expected to engage in “discovery of regularities of previously unrecognized relations” (64). The notion that instructors could guide students through a process of discovery was expressed in the three-phase “learning cycle” propounded by Robert Karplus (65). In this cycle, students’ initial exploration activities led them (with instructor guidance) to grasp generalized principles (concepts) and then to apply these concepts in varied contexts. These ideas of inquiry-based “active” learning could themselves be traced back to workers who came much earlier, including Piaget (66) and his followers, and to proponents of the ancient notions of Socratic dialogue. Piaget’s emphasis on the importance of explicitly cultivating reasoning processes that employed hypothesis formation, proportional reasoning, and control of variables later had an enormous influence on both physics and chemistry educators (67).

Inspired in part by Piaget’s earlier groundbreaking investigations, science educators began to perceive the pedagogical importance of the ideas that students brought with them to class. Piaget had emphasized that new ideas being learned had to be “accommodated,” in a sense, by a student’s already-existing ideas (66). As Bruner put it, the learning process at first involves “*acquisition* of new information—often information that runs counter to or is a replacement for what the person has previously known implicitly or explicitly. At the very least it is a refinement of previous knowledge” (68). Later, researchers began systematic efforts to probe students’ thinking on a variety of science topics, initially at the elementary and secondary levels (69). In the late 1970s, Viennot (70) in France and McDermott and her students in the United States (71) were among the very first to systematically investigate understanding of science concepts by students enrolled in university-level courses. These investigations led immediately to the development and implementation of research-based instructional methods and curricula.

McDermott’s research formed the basis for development of curricular materials that explicitly addressed students’ pre-instruction ideas. The research-based materials guided students both to elicit their pre-instruction ideas, and then to carry out the thinking processes needed to resolve conceptual and reasoning difficulties that emerged during the instructional process. By doing this research and then bringing to bear on university-level science instruction the pedagogical perspectives and methods employed earlier for younger students, McDermott and other physicist-educators “closed the circle.” They had laid the foundation for an ongoing process of research and reform in science education that could engage all participants in the process from the elementary grades on through graduate school. It is on this foundation that the present project is built.

Figure Caption

Figure 1. Sequence of “flash-card” questions for interactive lecture, showing student response rates (obtained at Iowa State University); three pages from Chap. 3 of “Workbook for Introductory Physics” by D. E. Meltzer and K. Manivannan.

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Chapter 3 Electric Potential Energy

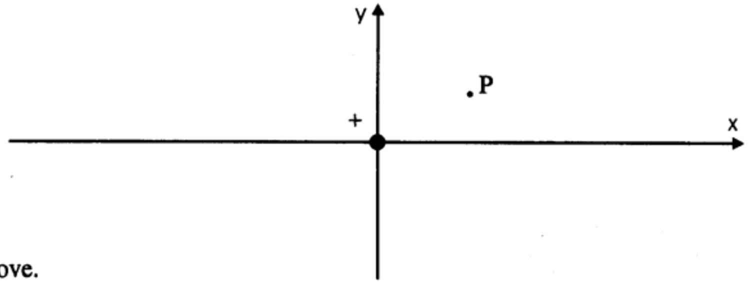
In-Class Questions

Prerequisite Concepts:

- **Positive and negative charge; Coulomb's law**
- **Definition of electric field**
- **Electric field of a parallel plate capacitor**
- **Kinetic energy and mechanical potential energy**
- **Definition of work; work/energy relationship**
- **Conservative forces/conservation of total energy**
- **Electrical force is conservative**

[Note: All gravitational forces may be ignored in this chapter]

1. *(Questions #1–6 refer to this figure.)* This figure shows a positive charge that is ***fixed in position*** at the origin. Suppose a positive charge q is placed at position P, and then released so that it (the charge q) is free to move. What will happen to this charge q?



A. It will not move.
B. It will move closer to the origin.
[✓ C.] It will move farther away from the origin.
D. It will start moving closer to the origin, but then will reverse direction and start moving back out again.
E. It will start moving away from the origin, but then will reverse direction and start moving back in again.

#1:

A: 0%
B: 7%
C: 93%
D: 0%
E: 0%

2. As the charge q moves, what will happen to the magnitude of the electrical force acting on it?

A. The force will remain constant.
B. The force will increase in magnitude.
[✓ C.] The force will decrease in magnitude, but never quite reach zero.
D. The force will decrease in magnitude, and at a certain point will reach zero.
E. The force will begin to decrease in magnitude, but then will start to increase again.

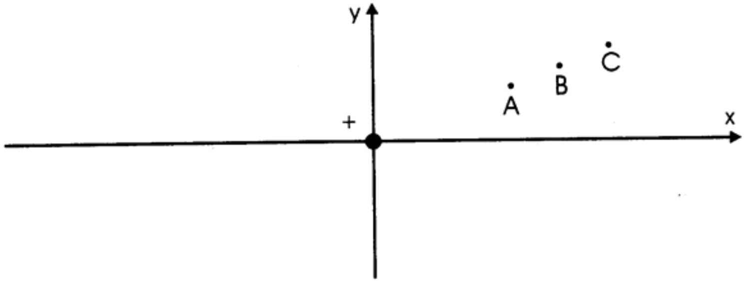
#2:

A: 10%
B: 8%
C: 77%
D: 2%
E: 5%

#7:

A: 2%
B: 3%
C: 3%
D: 83%
E: 9%

7. *(Questions #7–10 refer to this figure.)* In this figure (as in the previous one) a positive charge is fixed in position at the origin. Suppose a positive charge q is held at rest at position A, and then released and allowed to move freely. It passes through position B, and then moves on toward position C. Which of the following statements about charge q is true?



A. Its kinetic energy is the same at B and A, and its electric potential energy is the same at B and A.
B. Its kinetic energy is larger at B than at A, and its electric potential energy is larger at B than at A.
C. Its kinetic energy is smaller at B than at A, and its electric potential energy is smaller at B than at A.
[✓ D.] Its kinetic energy is larger at B than at A, but its electric potential energy is smaller at B than at A.
E. Its kinetic energy is smaller at B than at A, but its electric potential energy is higher at B than at A.

#8:

A: 0%
B: 2%
C: 8%
D: 87%
E: 3%

8. This question again refers to the situation in Question #7. In comparing the energy of the charge q at positions C and B, which of the following statements is true?

A. Its kinetic energy is the same at C and B, and its electric potential energy is the same at C and B.
B. Its kinetic energy is larger at C than at B, and its electric potential energy is larger at C than at B.
C. Its kinetic energy is smaller at C than at B, and its electric potential energy is smaller at C than at B.
[✓ D.] Its kinetic energy is larger at C than at B, but its electric potential energy is smaller at C than at B.
E. Its kinetic energy is smaller at C than at B, but its electric potential energy is higher at C than at B.

#9:

A: 0%
B: 13%
C: 7%
D: 53%
E: 22%

9. Again consider the setup shown in Question #7. Suppose now that a positively charged particle is shot from a gun that is located far away from the positive charge at the origin, but which is aimed directly at it. After leaving the gun the particle heads toward the origin, passing first through position C, then position B, and then position A. In comparing its energy at positions C and B, which of the following statements is true?

A. Its kinetic energy and electric potential energy are both the same at C and B.
B. Its kinetic energy and electric potential energy are both larger at C than at B.
C. Its kinetic energy and electric potential energy are both smaller at C than at B.
[✓ D.] Its kinetic energy is larger at C than at B, but its electric potential energy is smaller at C than at B.
E. Its kinetic energy is smaller at C than at B, but its electric potential energy is higher at C than at B.

#10:

A: 67%
B: 20%
C: 9%
D: 2%
E: 0%

10. Consider the situation described in #9. Let us call the ***magnitude*** of the change in kinetic energy $|\Delta KE|$, and the ***magnitude*** of the change in electric potential energy $|\Delta PE|$. Which of these is true about the energy of the particle shot from the gun, as it travels from position C to position B?

[✓ A.] $|\Delta KE| = |\Delta PE|$
B. $|\Delta KE| > |\Delta PE|$
C. $|\Delta KE| < |\Delta PE|$
D. Not enough information to answer.