Chapter 6. Open Ended Written Assessments: Quizzes and Exams

I. CHAPTER OVERVIEW

While surveys and diagnostics are useful for determining the students' initial state and changes that occur during the introductory sequence, more traditional assessments like exams and quizzes also have a role in determining what students know and what they are learning. The open-ended questions used in quizzes and exams often require deeper thinking from the students and can reveal more about how students understand and reason with the course material than do multiple choice questions. In this chapter, we look at how exams and quizzes can be used more effectively to evaluate what students are learning in introductory physics courses. In order to understand how they can be used to tell us more about student learning, it is useful to recap briefly some of the research on problem solving and learning.

As we saw in chapter 2, there are significant differences between novice and expert problem solvers. In addition to having more and better organized physics knowledge, expert problem solvers make heavy use of qualitative descriptions of the problem both in forming the solution and evaluating the answer.[1] This requires a good conceptual understanding and the view that physics is a coherent framework of a few key principles that can be used to understand real world phenomenon. Experts also make use of a problem solving strategy like the one shown in Table 2-1.

In contrast, at the beginning of the introductory course, many students solve physics problems by looking for equations that contain the unknown quantity and working backwards or looking in the text for examples that are similar. During the introductory sequence, most students at some point learn to classify and approach physics problems according to their surface features. The best students develop the ability to classify and solve problems according to the physical principles involved. These students are developing a more expert view of problem solving.

It is too much to expect that the introductory physics sequence can turn students from novice problem solvers into experts. However, it is appropriate as one of our main goals for the introductory physics sequence to help students begin developing the skills and attitudes needed to become expert problem solvers. Note that these skills and attitudes that instructors would want their students to develop to achieve this goal are part of the hidden curriculum that often aren't demonstrated, explicated, or reinforced through graded assignments to the students. For example, three of these skills and attitudes could be to have students achieve the following:

1. understand and use the principles, concepts, and laws of physics
2. develop an expert-like problem solving strategy
3. link problems to other contexts including real world applications

This chapter discusses some ways in which exams and quizzes can be used both to help students reach these goals and to learn more about how they think about physics along the way. In section II, I discuss some of the difficulties with traditional textbook problems. This is illustrated with a student's response to a traditional problem and a qualitative problem on the same exam. Some alternative problem styles are presented as examples of how exam problems can be used to determine more of what students are thinking.

In section III, I discuss how conceptual quizzes can be used to see what students are thinking during instruction so that the instruction can be tailored to where the students are. The results of two pretests, conceptual quizzes associated with University of Washington Tutorials, from classes at University of Maryland are presented. The first pretest inquires into students' conceptual understanding of Newton's Laws. The second pretest looks at students' mathematical understanding of what it means when one equation is the solution to another. The last section summarizes the chapter with a discussion on what quizzes and exams can tell us about student learning.

II. EXAM PROBLEMS

A. Traditional Textbook Problems & Qualitative Problems

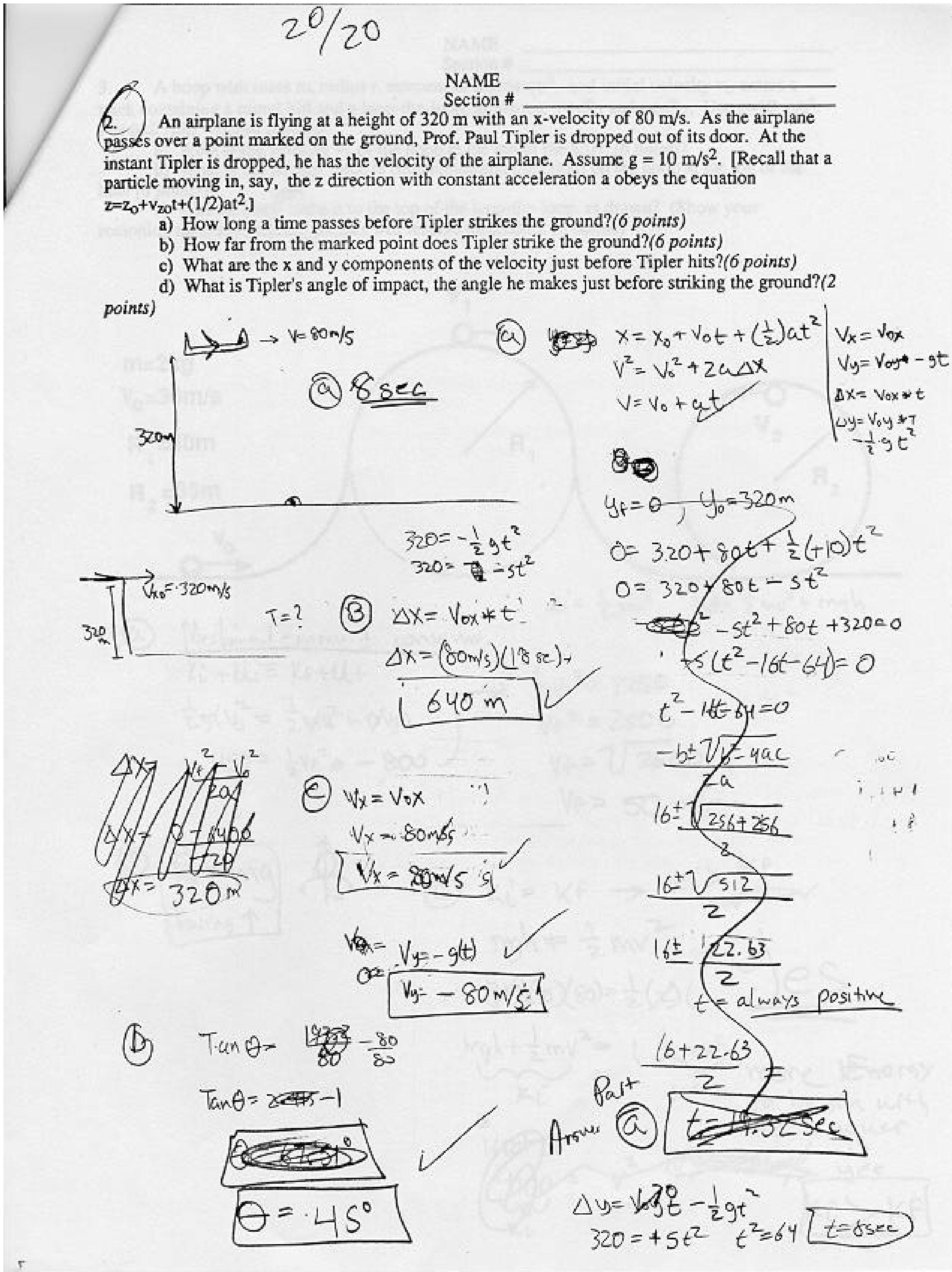
One difficulty with many textbook problems is that they can be solved by students by just finding an equation that contains the unknown quantity, plugging in the given quantities, and calculating a numeric answer. These problems do not require much conceptual understanding or decision-making on the part of the students.[2] In this dissertation, problems like this are referred to as "traditional textbook problems".

If instructors' goals for students go beyond solving traditional textbook problems, then using these types of problems almost exclusively on homework, quizzes, and exams may not be the best way to help them achieve the course goals. There are two reasons for this, one from a pedagogical standpoint and one from an assessment standpoint. First, from a pedagogical standpoint, traditional textbook problems encourage a mechanical, mathematical, algorithmic approach to problems solving. This in turn encourages the use of the novice strategies discussed above. As shown in the examples of Mazur and Hammer in chapter 2, students using this type of approach can often solve the problem and obtain an answer without understanding the underlying physics. Heller and Hollabaugh found that even when working in groups, students focus on the formulas and the calculations with little discussion and evaluation when they solve textbook problems. Tobias' observers noted that in their physics courses, the near exclusive use of these textbook problems on homework and the use of simple versions on exams seemed to affect the course goal in the minds of many of their classmates. These students' course goal was not to understand the physics concepts and use them to understand phenomena, but to learn to solve the textbook problems with minimal effort.

Second, from an assessment standpoint, traditional textbook problems are not always good indicators of what students know and understand. Because students can often solve these problems without much consideration of the underlying physics, the written solutions may not show much of how students think about and use physics concepts and representations. We saw examples of this in the studies by Mazur and Hammer in chapter 2. In both cases, assessment by traditional textbook problems failed to indicate significant student difficulties with the course material.

The responses of a single student to two problems (out of seven) on a final exam shown in Figures 6-1 and 6-2 are a case in point. The exam was given at the end of the first semester introductory physics sequence for engineering majors at University of Maryland. The problem shown in Figure 6-1 is a typical textbook-style problem on projectile motion. The problem shown in Figure 6-2 is a qualitative problem I wrote to look at students' understanding of Newton's 2^{nd} & 3^{rd} laws and velocity graphs. Note

Figure 6-1. Student solution to a traditional textbook style problem. This problem looks at student understanding of projectile motion. Notice that there is no mention of force.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2. An airplane is flying at a height of 320 m with an x-velocity of 80 m/s. As the airplane passes over a point marked on the ground, Prof. Paul Tipler is dropped out of its door. At the instant Tipler is dropped, he has the velocity of the airplane. Assume $g = 10$ m/s^2. [Recall that a particle moving in, say, the z direction with constant acceleration a obeys the equation $z=z_0+v_{z0}t+(1/2)at^2$.]

a) How long a time passes before Tipler strikes the ground?*(6 points)*

b) How far from the marked point does Tipler strike the ground?*(6 points)*

c) What are the x and y components of the velocity just before Tipler hits?*(6 points)*

d) What is Tipler's angle of impact, the angle he makes just before striking the ground?*(2 points)*

Figure 6-2. Student solution to a qualitative exam problem. The problem is designed to look at student understanding of Newton's 2nd & 3rd laws and velocity graphs.

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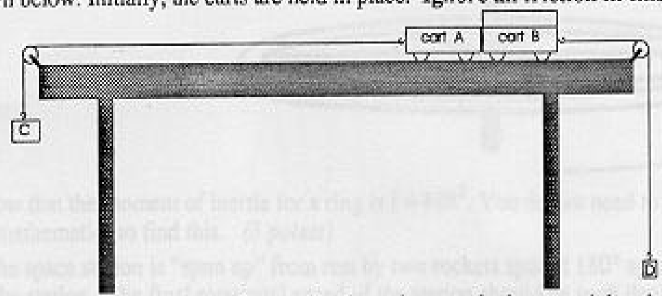
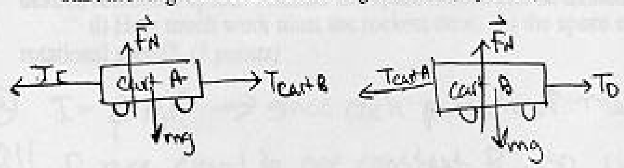
4. Two carts, A and B ($Mass_A < Mass_B$), are placed on a table then stuck together with Velcro. Using pulleys, two small blocks, C and D ($mass_C > mass_D$), are connected by light strings to the carts as shown below. Initially, the carts are held in place. **Ignore all friction in this problem.**



At t = 0, the carts are released. At t = 3 seconds, the string attached to cart A breaks. At some later time, the carts return to their starting point.

a. Draw and label two separate free-body diagrams, **one for each cart**, for a time after the carts start moving but before the string breaks. *(7 points)*



b. Rank all the horizontal forces from both your diagrams by magnitude, from largest to smallest. **Explain the reasoning that you used to rank the forces.** *(7 points)*

All horizontal forces = Tc + TD, Tcart B, Tcart A.

Tc > TD > Tcart A > Tcart B

Because T[D] is heavist & moves the whole system to left.
Then TD is 2nd heavist & moves the system back to original position.
Tcart A is 3rd " because cart A is lighter than cart B & because cart A is lighter, gives Tcart A lager magnitude. And last only Tcart B is left so it is last.

c. Briefly describe the motion of cart B from t = 0 until it returns to its starting point. On the graph below, qualitatively sketch the velocity vs. time for this time period. *(6 points)*

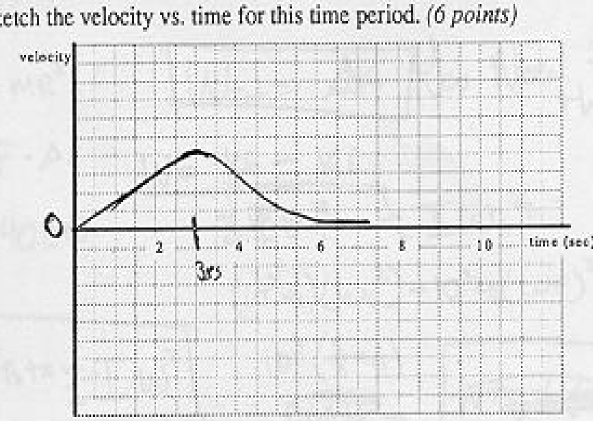
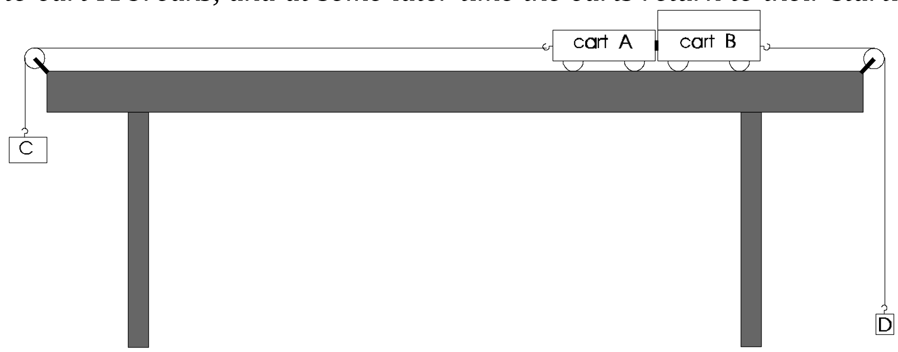


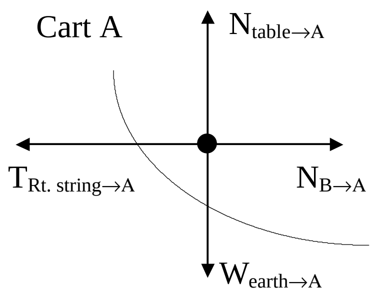
Figure 6-3. A correct solution to the qualitative problem in Figure 6-2a

We are given that $Mass_A < Mass_B$ and $mass_C > mass_D$ *and that we can ignore frictional forces. We are told that at* t = 0 *the carts are released, at* t = *3 seconds the string attached to cart* A *breaks, and at some later time the carts return to their starting point*.

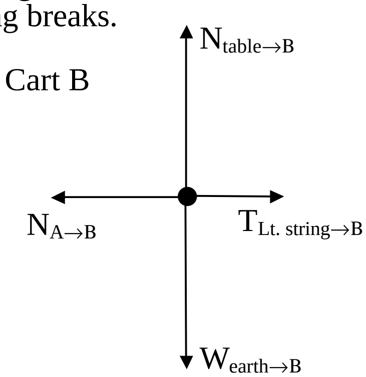


a. Draw and label two separate free-body diagrams, **one for each cart**, for a time after the carts start moving but before the string breaks.

Cart A



Cart B

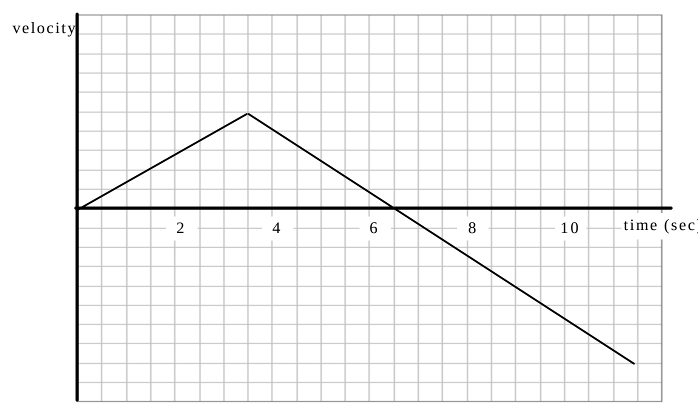


b. Rank all the horizontal forces from both your diagrams by magnitude, from largest to smallest. **Explain the reasoning that you used to rank the forces**.

$T_{string \to A} > N_{A \to B} = N_{B \to A} > T_{string \to B}$ *Because* $m_c > m_d$ *, the two carts accelerate to the left after they are released. Since both carts accelerate to the left by Newton's* 2nd *law again, there is a net force on each cart to the left*. => $T_{string \to A} > N_{A \to B}$ *and* $N_{B \to A} > T_{string \to B}$. *And from Newton's 3rd law we know* $N_{A \to B} = N_{B \to A}$.

c. Briefly describe the motion of cart B from t = 0 until it returns to its starting point. On the graph below, qualitatively sketch the velocity vs. time for this time period.

The carts accelerate (constant acceleration) to the left after they are released until the string breaks. Then the carts slow down, stop, and accelerate to the right eventually reaching their starting point. After the string breaks acceleration is constant pointing to the right.



that unlike most textbook problems, there are no numbers and the motion is described in detail qualitatively. A correct solution for the qualitative problem is shown in Figure 6-3. Let's see how the student approached the two problems.

In the textbook problem, the student starts by drawing a picture using the information given in the problem. Then the student writes down the three kinematic equations as they can be found in any textbook. Then the initial values are plugged into the general displacement equation. At this point the student did not recognize that the initial y velocity is zero. The student solves the rest of the problem before realizing this mistake. Then the student writes down the equations for the x and y components of displacement and velocity. The y displacement equation is used to solve for the time of flight. The student again proceeds to answer the remaining three parts of the problem. Notice that once the equations are written down and the initial conditions are plugged in, the student treats the rest of the solution as a mathematical exercise except for noting that time is always positive. However, the student changes the sign in the y displacement equation at the bottom of the page and ignores the minus sign in the answer for the y-component of velocity. These indicate that the student is not using a consistent coordinate system with respect to the y-coordinate and perhaps not relating the given quantities to the physical situation defined by the problem. However, as far as the problem and the grader are concerned, this student has demonstrated a good understanding of projectile motion.

For the qualitative problem, the student draws the free-body diagrams, ranks the forces, and draws the velocity graph. The free-body diagrams have the correct number of forces and the forces are labeled more or less correctly by type and magnitude. Force vector lengths do not seem to be drawn to scale. However, in ranking the forces the student ignores Newton's laws of motion and uses two common sense beliefs. One, the system moves in the direction of the largest force and two, the heavier mass exerts the larger force. At first glance, the velocity graph looks correct but incomplete. However, the velocity goes to zero at t = 6 seconds and appears to stay there. Without the requested description of the motion it is hard to be sure, but other students who answered this way indicated that the second point where v = 0 is where cart B returns to its starting point. This would be consistent with kinematic graph difficulty discussed in chapter 2 where the students thought of velocity graphs as "pictures of the motion" and drew velocity graphs that are really position graphs.[3] If this was the case here, the student may be indicating that the two carts move with constant velocity to the left and then move with constant velocity to the right. Note that there is no indication in part b that the carts are accelerating. An analysis of the 2-cart qualitative problem shown in Figure 6-2 for traditional and tutorial classes at University of Maryland is discussed in chapter 9.

We see that the one-dimensional qualitative problem is a better indicator of this student's difficulty with the course material than the two-dimensional textbook-style problem. The student's solution to the qualitative problem indicates difficulties both with velocity graphs and with Newton's Laws while the solution to the projectile motion problem only indicates a difficulty with applying a consistent coordinate system. However, qualitative problems are only one way to look at what students are learning. Other types of problems that can be used for this purpose including essay questions and estimation problems.

B. Essay Questions

As Tobias' student observers commented in chapter 2, most traditional physics lecture courses do not provide much opportunity for students to discuss and debate the material. The emphasis on traditional quantitative problems also does not provide many opportunities for students to write about physics and what they are learning, even sometimes in courses where laboratory reports are required. Writing requires students to think about physics in a less mathematical way and can help students recognize the implications of what they are learning. Writing assignments also can help instructors understand how students think about specific physics concepts.

As discussed in chapter 3, one method to introduce more writing into the introductory physics class is to require the students to keep journals.[4] Another method is to ask essay question on homework and exams. Two examples of essay exam questions used by Redish[5] at University of Maryland are shown below:

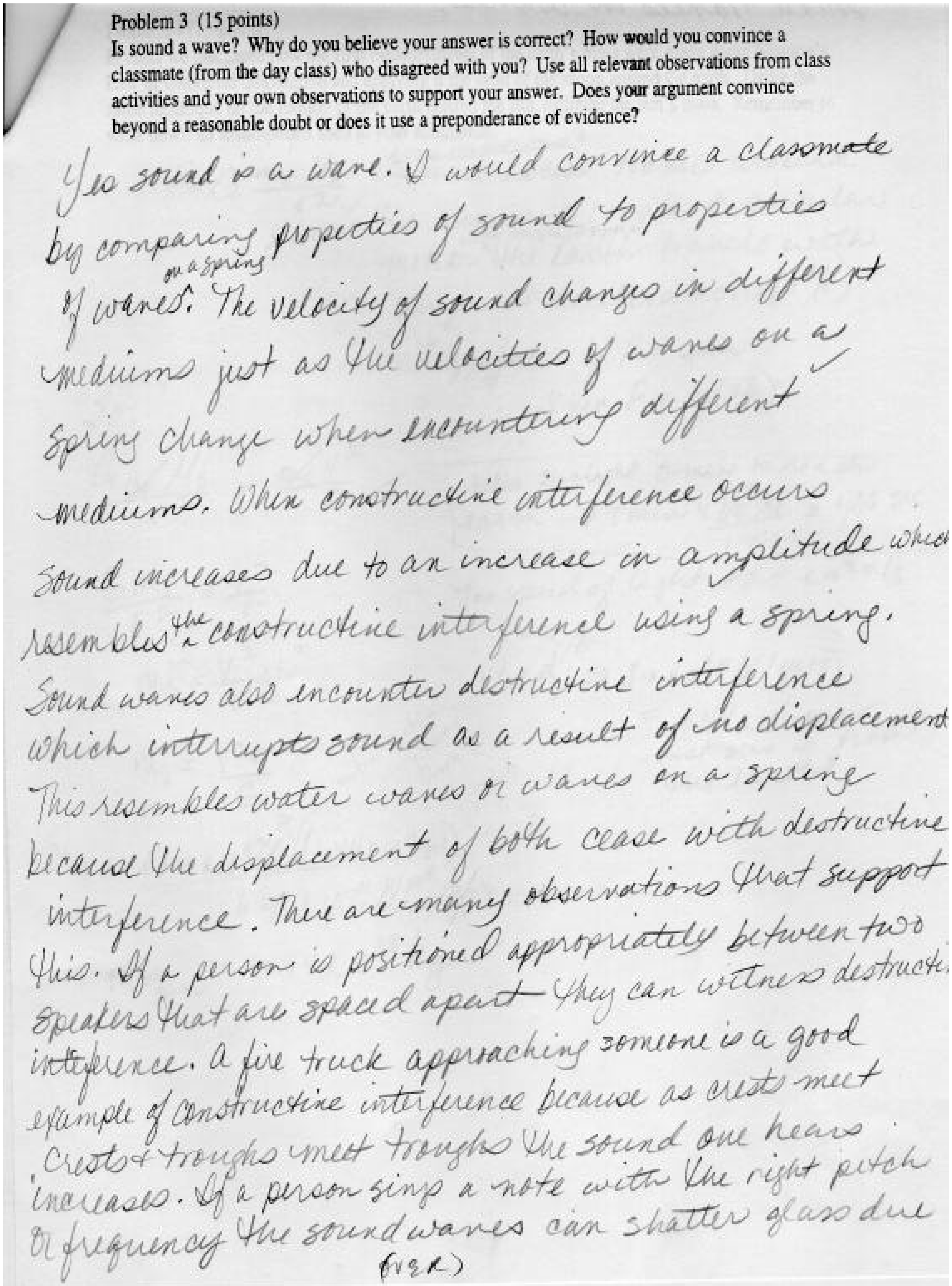
1. Newton's first law states an object will move with a constant velocity if nothing acts on it. This seems to contradict our everyday experience that all moving objects come to rest unless something acts on them to keep them going. Does our everyday experience contradict one of Newton's Laws? If it does not, explain the apparent contradiction. If it does, explain why we bother to teach Newton's first law anyway.
2. Define and discuss what we mean by an electric field.

In his instructions on exams and homework, Redish encouraged his students to cite examples and demonstrations used in class. For the first question, students needed to reconcile their real world experience with textbook physics by understanding the role of friction in everyday motion. The second question arose from concern that students in introductory physics have trouble with the concept of fields. When question 2 was given on an exam covering electric force and electric field, it brought out some student misconceptions such as defining the field as an area or a volume and confusion over the role of the test charge.

A third example of an essay question that I wrote to look at students understanding of the nature of waves is shown with a student response (from an algebra/trig-based introductory course at a community college) in Figure 6-4.[6] In this question, the students were asked to use what they had learned in all aspects of the class on the nature of waves including laboratories, concept-building activities, demonstrations, and class discussions to support their answer. It asks the students to think about what they know and why they believe it. Note that in the student solution shown in Figure 6-4, the student correctly states that wave speed is a property of the medium and correctly describes constructive and destructive interference but incorrectly uses interference to explain the Doppler shift of a fire engine siren when it is moving towards the observer.

In each of the three examples, the essay questions ask students to relate either different concepts or different aspects of a concept in a single question. These types of questions encourage students to think about the concepts they are learning and how they relate to one another. They are an appropriate response to the comment by Tobias' observers (see chapter 2) that typical exam questions tend to require only the use of single concept in a simple context and do not require or encourage a good understanding of the course material.

Figure 6-4. Student response to an essay exam question on the nature of waves.



Problem 3 (15 points)
Is sound a wave? Why do you believe your answer is correct? How would you convince a classmate (from the day class) who disagreed with you? Use all relevant observations from class activities and your own observations to support your answer. Does your argument convince beyond a reasonable doubt or does it use a preponderance of evidence?

Yes sound is a wave. I would convince a classmate by comparing properties of sound to properties of waves on a spring. The velocity of sound changes in different mediums just as the velocities of waves on a spring change when encountering different mediums. When constructive interference occurs sound increases due to an increase in amplitude which resembles the constructive interference using a spring. Sound waves also encounter destructive interference which interrupts sound as a result of no displacement. This resembles water waves or waves on a spring because the displacement of both cease with destructive interference. There are many observations that support this. If a person is positioned appropriately between two speakers that are spaced apart they can witness destructi[ve] interference. A fire truck approaching someone is a good example of constructive interference because as crests meet crests & troughs meet troughs the sound one hears increases. If a person sings a note with the right pitch or frequency the sound waves can shatter glass due

(over)

C. Estimation Problems

Most physicists at some point in their career learn to sharpen their problem solving and thinking skills by working what are known as Fermi, order of magnitude, or estimation problems. These problems are useful because they require the solver to

- pull together knowledge from several contexts,
- think about how to estimate reasonable values for numbers, and
- relate knowledge from formal instruction to real world situations.

However, these problems are not necessarily just for physicists. Estimation problems can be written at a level appropriate to an introductory physics course and used to encourage the development of the above skills in non-physics majors. This type of problem allows the students to practice applying what they learn in new and sometimes more realistic contexts but not at a significantly greater level of difficulty. By seeing how the students apply equations and concepts out of the context in which they were learned, the instructor can get insight into how the students think about the concepts. Some examples of estimation problems are shown below in the order they might appear in an introductory physics sequence.[7]

1. You and a friend are planning a two-week vacation out to the West Coast for a wedding next summer. However you're both on a tight budget. Your friend thinks it would be cheaper to drive his car than fly. A cheap plane fare from BWI to San Francisco is $350 round trip. Realistically estimate your travel expenses to drive to and from the West Coast to see if your friend is right. What would your average speed be? Assume you will have free room and board at a relative's house once you arrive.
2. This winter, the East Coast has been hit by a number of snowstorms. Estimate the amount of work a person does shoveling the walk after a snowstorm. Among your estimates you may take the following:
    - The length of a typical path from a house to the street is 10 meters.
    - Assume the snow fell to a depth of 4 inches.

- Assume the snow was only moderately packed so that its density was equal to 0.2 g/cm^3 – about one fifth that of water.

In doing this problem, you should estimate any other numbers you need to one significant figure. Be certain to state what assumptions you are making and to show clearly the logic of your calculation. (In this problem, the answer is only worth 2 points. Almost all of the credit is given for your showing correct reasoning clearly.)

3. For next year's Physics Open House the department is planning to set up a bungee jump from the top of the physics building. Assume that one end of an elastic band will be firmly attached to the top of the building and the other to the waist of a courageous participant. The participant will step off the edge of the building to be slowed and brought back up by the elastic band before hitting the ground (we hope). Estimate the length and spring constant of the elastic you would recommend using.
4. A typical television tube works by accelerating electrons through an electrostatic potential and then bending them with a magnetic field as shown in the figure at the right. If the electrostatic potential difference used to accelerate the electrons through the anodes is 10,000 Volts, estimate the maximum strength of the magnetic field needed to control the deflection of the electron beam. Use your experience with television sets to choose reasonable parameters for the distances required.

The first three have been used as exam problems; the fourth has only been used as a homework problem. Notice that the problems increase in both complexity and the amount of thought required to solve the problem as the student moves through the introductory physics sequence.

I wrote the first example problem to see how my students in the community college class would use the concepts of velocity and average velocity in a realistic scenario where they cared about the quantity in question, i.e. money. For the most part, the students made reasonable assumptions and calculations in solving the problem although some had difficulty with what was meant by average velocity.

The other three questions were written and used by Redish in the engineering physics sequence at University of Maryland. The problem on calculating the work while shoveling snow produced some interesting student views on work and how to calculate it. Some students (10% with grades ranging from F to A) responded with how much effort or time the job would take. Some students used Work = force x distance and then calculated the work as W = mgd where d was the length of the walk. For the bungee jumper/harmonic oscillator problem, many students assumed the maximum stretch would occur when the gravitational force on the jumper is equal in magnitude to the spring force on the person rather than when the spring potential energy equals the initial gravitational potential energy of the jumper. The fourth problem proved to be especially difficult for many students because of the number of relationships required between the length of the tube, the length of the applied magnetic field, and the strength of the magnetic field.

In each of the four problems the students are asked to apply their physics knowledge to new, applied contexts. Note that the concepts and equations are used in the same way the students learned them, but now the students must make decisions as to what concepts and equations apply to the problem. Based on the work of Heller *et al*. reported in chapter 2,[8] I believe the decisions the students make in terms of what knowledge they should use, what information is needed, and what quantities need to be estimated encourage the development of expert problem solving skills. Because the students draw on their own experience to visualize the problem situation and develop a sense of real world numbers, estimation problems may help the students link the classroom physics to their everyday world. As an assessment tool, they can help instructors see how students use what they know outside the familiar context of the textbook and lecture.

III. CONCEPTUAL QUIZZES

A. What is a Conceptual Quiz/Pretest?

Based on the findings of Physics Education Research discussed in chapter 2, instructors need to know what students are thinking to effect real change in the students' views and their working knowledge. However, since exams usually follow instruction on a topic, they come too late for instructors to see what students are thinking while they are still teaching a topic. While a pre-course diagnostic can be used to this purpose to some degree, it would be useful to be able to assess student thinking to determine what students believe coming into the class and how they are interpreting what they have learned in the class before the instructor starts on new material. Weekly quizzes with textbook-style problems have attempted to fill this role in some traditional physics courses. But as discussed in the previous section, this type of problem is often more a measure of whether the students recall a similar problem rather than a measure of how students are thinking about the course material. To see how students are thinking about the course material as it is being taught, both Mazur[9] and McDermott[10] have incorporated conceptual quizzes into the research-based curricula they each developed, Peer Instruction and Tutorials, respectively. Since Mazur's peer instruction curriculum is not a subject of my investigation, only the conceptual quizzes used in Tutorials will be discussed here. In McDermott's tutorial curriculum, these conceptual quizzes are called pretests.

The tutorial method was developed by McDermott's Physics Education Group at the University of Washington to address students' difficulties with physics concepts and representations.[11] As a result, their pretests are designed to assess these student difficulties. In the tutorial curriculum, the traditional problem solving recitation is replaced with a cooperative group activity where the student groups go through worksheets designed to help the students confront and resolve difficulties caused by their common-sense beliefs. (The tutorial curriculum is discussed in more detail in chapter 8.) The instructor becomes a facilitator helping the students understand the implications of what they are learning by asking questions. To help the facilitators learn how the students are thinking about the material going into the tutorial, a pretest is given in lecture before the students start doing the tutorials in their recitation sections. Ideally the pretest for a specific topic is given after the students have seen the material in lecture but before they work on it in tutorial. The students receive credit for taking the pretest, but they are not graded on what they write. This allows the students to write what they think without the penalty of being marked down for it.

The pretest is typically given in the first 10 minutes of a lecture class once a week. The questions are designed, not only to help the instructors understand how students are thinking about a particular topic, but also to help the students start thinking about some of the issues that will be addressed in the coming tutorial. The tutorial instructors meet after the pretest was given and before the tutorials start for that week to go over both the student pretests and the tutorial. One of the TAs does a quick tally to identify the most common student difficulties. This identifies key issues the tutorial instructors will want to make sure their students address in their tutorial sections.

At University of Maryland, we use some of these tutorials as well of some of our own using MBL and multimedia tools. We also use some group problem solving tutorials to help students integrate the concepts with problem solving. The pretests for problem solving tutorials often address more mathematical student difficulties. Examples of a conceptual pretest and a mathematical pretest are given below.

B. Conceptual pretest example: Newton's third law

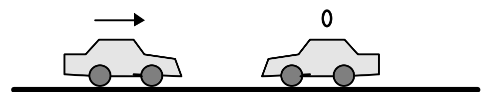
Newton's third law is quite possibly the most difficult mechanics concept for students in introductory physics classes to understand and accept.[12] To address this difficulty, I wrote a Newton's third law pretest and tutorial using two carts and MBL force probes for the first semester of the introductory physics class for engineers at the University of Maryland.[13] The pretest questions from the 1995 fall semester are shown in Figure 6-5 on the next page. Post-course results from this semester including the exam problem that looks at student understanding of Newton's third law in Figure 6-2 are discussed in chapter 9. This pretest was given in the sixth week of the semester after Newton's laws of motion had been covered in lecture. The results of a quick tally from the pretest are shown in Figure 6-6. The actual pretest is shown in Appendix D.

The quick tally of the students results from this pretest are summarized below (percentages are rounded to the nearest five percent):

- In a collision between two cars where the one on the left is stationary, only 40% of the students correctly stated that the forces the two cars exert on one another are equal. Another 40% clearly state the force of the moving car on the stationary car is larger because it is moving.
- Only 15% of the students said the forces in a head-on collision between a moving van and a car moving with the same speed were equal. Almost two thirds of the students (65%) answered that the force exerted by the van on the car would be larger. Their reasoning was that the heavier object should exert a larger force.
- Only 20% of the students were able to correctly state Newton's third law in their own words. Almost a third of the students (30%) used Newton's second law to justify the third or referred to the two forces as acting on one object.

Figure 6-5. Newton's third law pretest used in several first semester classes of the introductory physics sequence for engineering majors at the University of Maryland from 1994-1995. This pretest was used to assess student understanding of Newton's third law before they worked an MBL tutorial to help them better understand the concept. Note that the students are asked to rank the forces in part I-B. This allows the students to think about the relative size of the forces without calculations.

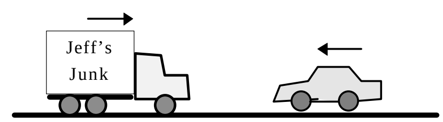
I. There is a collision between two cars of equal mass where one car is initially at rest.



A. Draw a free body diagram for each car during the collision showing all forces.

B. Rank the magnitudes of all the horizontal forces and give your reasoning.

II. Now think about a head-on collision between a moving van and a Ford Escort. Each vehicle is initially moving at the same speed. The following questions refer to what is happening during the collision.



A. Does the moving van exert a force on the Ford Escort?

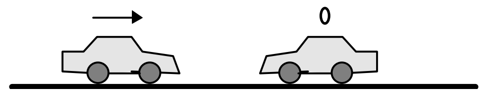
B. Does the Ford Escort exert a force on the moving van?

C. If the answers to questions A and B are yes, which force is larger?
Explain your answers to A, B, and C.

III. Write out a complete statement of Newton's third law in terms of forces in your own words. (You may use a diagram if you wish.)

Figure 6-6. Quick tally of the 86 student responses from the fall 1995 semester to the Newton's third law tutorial pretest shown in Figure 6-5.

I. There is a collision between two cars of equal mass where one car is initially at rest.



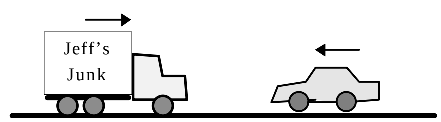
A. Draw a free body diagram for each car during the collision showing all forces.

- *Correct* - 23 students
- *Drawing Newton 3 pairs on the same system* - 27 students
- *Use of impetus force (force is proportional to velocity)* - 15 students
- *Drew a force due to acceleration* - 9 students
- *Other errors or blank* - 10 students

B. Rank the magnitudes of all the horizontal forces and give your reasoning. (The moving car is car a)

- *(Force of a ® b) = (Force of a ® b)* - 36 students
- *(Force of a ® b) > (Force of a ® b)* - 36 students
  This response was justified by the car's motion
- *Other* - 7 students
- *Blank* - 7 students

II. Now think about a head-on collision between a moving van and a Ford Escort. Each vehicle is initially moving at the same speed. The following questions refer to what is happening during the collision.



A. Does the moving van exert a force on the Ford Escort?
B. Does the Ford Escort exert a force on the moving van?

2 students said no, but it is not clear if they understood the questions

C. If the answers to questions A and B are yes, which force is larger?

- *The moving van exerts a larger force* - 54 students
- *The two forces are equal* - 15 students
- *Blank and other* - 10 students

III. Write out a complete statement of Newton's third law in terms of forces in your own words. (You may use a diagram if you wish.)

- *Correct statement of Newton's third law* - 19 students
- *Using Newton 2 to justify Newton 3*
  (the two forces act on the same object) - 26 students
- *Action/reaction with no mention of force*
  or equal/opposite without specifying which object - 21 students
- *Other* - 5 students
- *Blank* - 15 students

- Another 25% of the students used the phrase action-reaction without mentioning force or the phrase equal and opposite without mentioning the objects.

Note that the use of the phrases "equal and opposite" and "action-reaction" by students is often an indication of student difficulty with Newton's third law.[14]

C. Mathematical pretest example: A solution and the wave equation

In the 1995 fall semester, I had the opportunity to test one of my hypotheses on one aspect of students' use of mathematics in physics classes: Do students understand what it means to say that an equation is the solution to or satisfies another equation? During the 1995 fall semester, Redish at University of Maryland spent a lot of class time in the second semester of the introductory physics sequence for engineers emphasizing the derivation, meaning, and solutions of the wave equation. In the week of the exam, while Redish was reviewing material in lecture to help students prepare for the midterm exam, Redish and I decided to implement a group problem-solving tutorial on oscillations and waves to help the students learn to apply the concepts they were learning in solving problems. (See chapter 8 for a description of the tutorial teaching method and the implementation at University of Maryland.) I wrote the tutorial including a pretest to test two aspects of the connections between the mathematical formalism and the concepts the students were learning on waves. One of the problems asked whether $y[x,t] = A \cos (kx + wt)$ is a solution to the wave equation and how would the student convince a friend of their answer. The questions from the pretest are shown in Figure 6-7 on the next page.

Initially, Redish objected that this problem might be too easy since students did not have to show that $y[x,t] = A \cos (kx + \omega t)$ could be expressed in the general form of a solution to the wave equation y[x,*t*] = *F*[*x* - *vt*] + *G*[*x* + *vt*], they could just take derivatives of equation 1 and substitute into equation 2. But that was the point of the pretest. Would the students know to use one of these two approaches to show that equation 1 was a solution to equation 2?

Of the 113 students who took the pretest, only 55% explicitly stated that *y*[*x*,*t*] was a solution to the wave equation including 3 students who said it looks correct. One third of the students did not answer the question explicitly and only 10% of the students answered "I don't know" or "no, it is not a solution." Based on the students' answers to this question, there seem to be no significant student difficulties except for not answering the question. If there was a question about what the student wrote and why in the analysis of the pretest, I assumed the student gave the correct response or used the correct reasoning.

Surprisingly, only one third of the students either described or attempted a process that would have led to a correct solution. The results can be summarized as follows:

- Approximately 25% of the students took a derivative of *y*[*x*.*t*]. Four-fifths of these students substituted these derivatives into the wave equation and one-fifth showed that the resulting equation was true.
- Another 5% of the students used the general solution to the wave equation to support their answer. Half of these students either stated or showed that *y*[*x*,*t*] could be expressed as part of the general solution.
- Another 2% said that they would show that *y*[*x*,*t*] is a solution by showing that it satisfies the wave equation but did not take derivatives of *y*[*x*,*t*] or compare *y*[*x*,*t*] to the general solution.

Figure 6-7. Mathematical reasoning with waves pretest.

SHOW ALL YOUR REASONING IN YOUR ANSWERS.

1. A friend in this class does not believe that

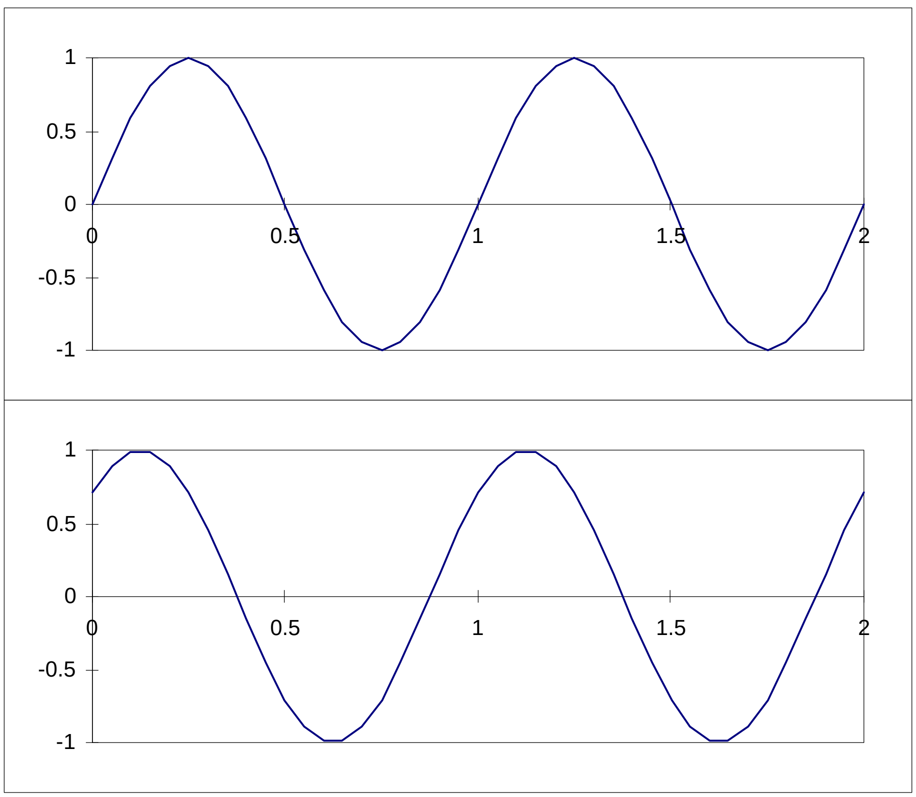
$$y[x,t] = A\cos(kx + wt) \qquad (1)$$

is a solution to the wave equation for the motion of a stretched spring,

$$\frac{¶^2 y}{¶x^2} = \frac{m}{T}\frac{¶^2 y}{¶t^2}\,. \qquad (2)$$

Do you think it is? Explain why you think so. How would you convince your friend of your answer?

2. A transverse wave is traveling on a long spring. A segment of this spring is shown at time t=0 in the first of the two figures below. The second figure shows what this segment looks like at time t = 0.01 s. The y-axis is in cm, while the x axis is in m.



Assuming that the wave continues in the way it is shown, write an equation that would allow you to find the displacement of the spring *y*[*x*,*t*] for an arbitrary position x, at an arbitrary time t.

The other students used a variety of approaches. It is interesting to note that other than no reason (20% of the students did not give any reasoning), the two most common incorrect responses were based on ideas that were emphasized by Redish in lecture.

- 15% of the students explained that $y[x,t]$ is a solution to the wave equation because the wave equation is really just a form of Newton's second law $F = ma$.
- 10% of the students used dimensional analysis of $y[x,t]$ or the wave equation in their reasoning.

D. Summary

It is becoming increasingly more accepted in the physics education community that effective instruction in the introductory class must take into account what students know and how they use what they know. Instructors often have a need to know more about what their students are thinking than can be learned with diagnostic and surveys instruments while they are teaching a topic. Conceptual quizzes like pretests can help meet this need by giving the instructor indications of what the students have learned and how they are using it.

Although pretests are usually used to assess well-known student difficulties with concepts and representations, they can also be used to assess students' understanding and use of mathematics in physics. It is widely believed by physics instructors based on anecdotal evidence that students' "mathematical knowledge" is often less than what would be expected from the list of prerequisites. Mathematical pretests like the one shown in this section can be used by instructors to better understand the mathematics difficulties of their own students.

However, pretests also have some limitations as well. First, pretests take class time to administer and analyze. As instructors struggle to cover all the required material in the introductory course and keep up with their hectic schedules, it is sometimes hard to find time for conceptual quizzes. Second, sometimes students don't reflect on what they are doing or just don't write explanations with their answers. Not much can be learned on student thinking when the students don't explain their answers. Third, the ten minute time limit and need to use the questions to bring students' attention to issues relevant to the coming tutorial restricts the type of questions that can be asked.

IV. WHAT CAN EXAMS AND QUIZZES TELL US ABOUT WHAT STUDENTS ARE LEARNING?

Many physics instructors use traditional textbook problems or minor variations to assess student learning. There are two problems with this. First, as we saw in chapter 2, the emphasis on this type of problem on homework and exams has been seen to encourage undesirable student attitudes towards problem solving and the course. These attitudes may limit what students learn. Second, and more importantly for research purposes, problems of this type often do not reveal much about how students think about the course material. Since students do not have to use their conceptual understanding, their solutions often emphasize the mathematical calculation and the numeric answer as we saw in the student solution to the projectile motion problem in Figure 6-1. To learn more about what students are thinking and learning, it is necessary to use problems where students explicitly show more of their reasoning.

Physics education researchers and instructors can learn more about what students are thinking by using problems that have one or more of the following properties:

- Problems that test conceptual understanding by having students construct physics representations like velocity graphs or free-body diagrams and compare quantities like the ranking of the horizontal forces acting on a pair of carts.
- Problems that require students to express their understanding in writing such as in short essay questions.
- Problems that get students to use what they know in new and more realistic contexts such as in estimation problems.

In this chapter, I have shown examples of how problems using these properties can identify and illuminate student difficulties with such basic concepts as velocity, Newton's laws of motion, the nature of the Doppler effect, and how to demonstrate that one equation is a solution of another. As we saw in the examples of Mazur, Hammer, and Tobias in chapter 2, few if any of these student difficulties would have been revealed by traditional quantitative textbook problems. That is not to say that quantitative problems are not useful from a research perspective, but they need to incorporate some or all of the above mentioned features and require more decision making than just finding the right equation to use.

Because students must give a solution that includes how they came up with an answer, quizzes and exams can be more informative than survey and diagnostics for showing what students are learning and thinking. However, even in quizzes and exams it is often hard to see how a student was thinking on a problem or why they answered a particular way. Here, the physics education researcher needs to resort to a method unavailable to most classroom instructors, interviews with the students.

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[1] D.P. Maloney, "Research of problem solving: physics," in *Handbook of Research on Science Teaching and Learning,* edited by D.L. Gabel (MacMillan Publishing Company, New York, 1994), 327-354.

[2] P. Heller and M. Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups, *Am. J. Phys.* **60** (7), 637-644 (1992).

[3] R.J. Beichner, "Testing student interpretation of kinematic graphs," *Am. J. Phys.* **62** (8), 750-762 (1994).

[4] F. Goldberg, "Constructing physics understanding in a computer-supported learning environment," in *AIP Conference Proceeding No. 399 The Changing Role of Physics Departments in Modern Universities: Proceedings of the International Conference on Undergraduate Physics Education*, edited by E.F. Redish and J.S. Rigden (AIP Press, Woodbury NY, 1997), 903-912; P. Hickman, "Alternative assessments: Insights into student learning," *AAPT Announcer*, **24** (2), 108 (1994, abstract only).

[5] Prof. E.F. Redish at the University of Maryland used these problems in the algebra/trig-based introductory course and the engineering introductory physics course.

[6] The O.J. Simpson civil trial concluded during this semester and as a class we had discussed the different standards of evidence used in the criminal and civil trials.

[7] For more problems and references on this topic, see the PERG estimation problem website at physics.umd.edu/rgroups/ripe/perg/fermi.html .

[8] See Ref. 2.

[9] E. Mazur, *Peer Instruction: A Users Manual* (Prentice Hall, New Jersey 1997).

[10] L.C. McDermott and P.S. Shaffer, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River NJ, 1997).

[11] See Ref. 9.

[12] R.K. Boyle and D.P. Maloney, "Effect of written text on usage of Newton's third law," *J. Res. Sci Teach*. **28** (2), 123-140 (1991); D.E. Brown, "Students' concept of force: The importance of understanding Newton's third law," *Phys. Ed*. **24** (6), 353-358 (1989); D.P. Maloney, "Rule-governed approach to physics: Newton's third law," *Phys. Ed.* **19**, 37-42 (1984).

[13] E.F. Redish, J.M. Saul, and R.N. Steinberg, "On the effectiveness of microcomputer-based laboratories," *Am. J. Phys*. **65** (1), 45-54 (1997).

[14] How student use language is often an indication of their understanding of concepts. This is a current area of physics education research and is not well understood. But many observations by the author and other members of a physics education research listserve have observed that students who use the everyday language of Newton's

third law, i.e. phrases like “equal and opposite” or “action-reaction” often do not have a good conceptual grasp of Newton’s third law.