Chapter 7: Understanding Student Thinking through Interviews

I. OVERVIEW

In the past three chapters we have discussed methods of assessment that are relatively easy to implement in most introductory physics courses. No change in class format or additional resources like instructor time are required to use specially designed exam problems that allow students to demonstrate a richer understanding of physics than is the case with most traditional textbook-style problems. While some class time and additional resources may be required to administer and analyze conceptual quizzes and pre/post surveys like the MPEX survey and the FCI, their impact on the course and the instructor is minimal. These methods are very useful to monitor how a class is doing and can be implemented by researchers and instructors fairly easily, but there is no substitute for interviews with students for understanding what individual students are learning and thinking.

From a students' solution to an exam problem, you can see the steps the student used to solve the problem and maybe some of the concepts that were used. In an interview, a researcher can ask the student questions to see

- why they answered the problem that way,
- what they were thinking as they solved the problem,
- how they interpret concepts and equations they used, and
- how they interpreted the question.

This type of understanding is often essential to physics education researchers to understand what individual student responses on exams, quizzes and diagnostics are telling us about students' understanding of the course material. For example, the understanding developed from interviews often provides a framework to interpret student exam solutions in areas where students have conceptual difficulties. In many cases, the incorrect student responses to a problem that encourages students to use their conceptual understanding are due to just a few common misconceptions. Interviews can also tell us why certain misconceptions occur, the difficulties they signify, and help researchers learn how to address them.

The use of interviews by physics education researchers led to much of the current understanding of student difficulties associated with problem solving, conceptual understanding, and expectation discussed in chapter 2. The research conducted in the early 1980s using interviews changed physics education research from studies that relied primarily on informal classroom observations of students to more detailed and systematic studies of how students think about physics. Many of these PER interviews are based on the technique developed by Piaget to study how children and adolescents reason in physical situations. (Many of Piaget's interviews are based on common physics problems.[1] Physics education researchers typically find the following three types of interviews to be the most useful: validation interviews, demonstration interviews, and problem interviews. Each type of interview serves a different research goal.

Validation interviews are used to check student interpretations of instruments. This is usually done in one of two ways. One approach is where the interviewer asks the subject about the instrument items and their responses directly. Another approach is to ask the students related questions and compare their responses with their responses to the instrument.

Demonstration interviews are used to probe students understanding and knowledge of the course material. In a demonstration interview the student is given a situation or an apparatus and asked a series of questions that relate to it. The interviewer guides the inquiry to probe the student's understanding of the situation until they know what the student thinks will happen and why. This type of interview is often used in studies of students' common sense beliefs and misconceptions.

Problem solving interviews are used to see how students use their knowledge and reasoning when they perform tasks like solving a physics problem. The student is given the problem or task and works on it while being observed by the interviewer. The interviewer may ask some questions, but most of the time the interviewer is a silent observer. This allows the observer to see how the student works through the task on his or her own. This type of interview was used in many of the problem solving studies described in chapter 2.

Physics education researchers generally use one of two basic interview techniques, question and answer and think aloud. In the question and answer technique, the subject responds to the interviewer's questions. The interviewer listens to the subject's response and may ask follow-up questions to clarify the response. In a think-aloud interview the students say whatever is going through their minds as they perform a task or answer a question. As some students find this difficult, I went over a copy of the hints[2] shown in Table 7-1 with students participating in think-aloud interviews for this dissertation. Note that students are requested not to elaborate on what they have already said. The primary task of the interviewer is to keep the student speaking. Most

Table 7-1. Think aloud hints given to students at the beginning of demonstration or problem solving interviews. The hints come from p. 33 of the D.N. Perkins, *The Mind's Best Work* (Harvard U.P., Cambridge, MA, 1981)

1. Say whatever is on your mind. Don't hold back hunches, guesses, wild ideas, images, or intentions.
2. Speak as continuously as possible. Say something at least every five seconds, even if only, "I'm drawing a blank."
3. Speak audibly. Watch out for your voice dropping as you become involved.
4. Speak as telegraphically as you please. Don't worry about complete sentences and eloquence.
5. Don't over explain or justify. Analyze no more than you would normally.
6. Don't elaborate on past events. Get into the pattern of saying what you're thinking now, not of thinking for a while and then describing your thoughts.

students have a tendency to draw within themselves when thinking about something difficult. Think-aloud interview protocols work best with individual students while question and answer interviews can be used either with individuals or groups.

In this chapter I describe the different types of interviews and protocols used in this study. In section II, I discuss the two MPEX protocols used to study student expectations. Section III goes over the interview protocol used to study students' conceptual understanding of physics. This section also includes the results of a demonstration interview concerning the mathematical description of a propagating pulse on a string. This study is used as an example to illustrate what can be learned from this type of interview.

All the students interviews used in this dissertation were videotaped and transcribed. The student volunteers were solicited by requests made in class and required to sign a release form before being taped. A copy of the blank release form is included in Appendix E.

II. EXPECTATIONS

As discussed in chapter 5, I conducted over one hundred hours of interviews with students in my study of expectations. Two different expectation interview protocols were used, the MPEX Survey protocol and the Open MPEX protocol. Both protocols use the question and answer technique. The MPEX Survey protocol is shown in Table 7-2. It was designed primarily to validate the MPEX survey and to understand the reasoning behind the student responses by going through the survey items. The Open MPEX protocol is shown in Table 7-3. This protocol was designed primarily to probe students' math expectations and expectations regarding the connections between physics and mathematics. The students were interviewed either singly or in groups of two, three, or in rare instances four.

A. MPEX Survey Protocol

My main goal in these interviews was to validate the survey items by listening to the students' interpretations of the survey items and explanations why they answered the items the way they did. This told me whether the students were interpreting the survey items as I intended and if their reasoning made sense in light of the survey item. These interviews also helped me understand more about the nature of student expectations, how expectations shaped students' view of the class, and what aspects of the class students felt helped or hindered their learning. The results from these interviews are reported in chapter 10.

Table 7-2. MPEX Survey protocol (Spring 1997 version) – This protocol is used to validate the MPEX survey and to study student expectations in the context of the survey items. The students are asked to complete a pencil and paper version of the survey and sign a release form before the interview starts.

Part 1. Background:
This is Jeff Saul. I'm here at <name of school> with <student code name> who is in <describe class> with Professor <Prof. name here>. The interview today will have three parts. I will start the interview by asking you some questions about your background. Then I will ask you some questions about your survey responses. In the last part of the interview I will ask you some questions about the class.

Background questions

- So, first off, tell me a little bit about yourself. Where'd you grow up?
- What math classes did you have in high school?
- What science classes did you have in high school? Did you have physics in high school? Did your physics class use calculus?
- What made you decide to come to college here?
- Is the class what you expected to be?

Part 2. MPEX survey items:
[In this section the students are asked to go over 15-30 of the MPEX survey items depending on the length of the students' responses and the available time for a particular interview. Items 1, 2, 5, 9, 12, 13, 14, 19, 21, 22, and 34 were asked in most interviews.] The students are asked to read the survey item aloud, read their response, and explain why they answered that way. If students change their minds because they misread the question, they are instructed to cross out their first response with a single line and circle their new response. If students change their minds after thinking about their reasoning, they are instructed to cross out the old number completely and circle their new response.

Part 3. Comments on instruction:
Questions

- What did you like about the class? What did you dislike about the class?
- What would you say is the most interesting or significant thing you've learned this year in physics class?
- Of all the activities you did as part of this class, which were most useful for learning physics? Which were least useful?
- Did you work with other people outside of class? On a regular basis?
- If you had to make one change to the class to improve it, what would it be?

Table 7-3. Open MPEX protocol – this protocol is used to study student expectations with an emphasis on the connections between math and physics.

1. How would you describe yourself (as a student)?
2. What is your major?
3. What made you decide to be a ___________ major?
4. What is math?
5. What do you like about math and what do you dislike about it?
6. Do you think math is useful? Give an example.
7. What do you consider to be some interesting or significant things you have learned in your math classes?
8. What has stayed with you from your school experiences in math and (physical) science classes?
9. Do you recall any topics or issues from one of your "early" math classes that you found particularly difficult or troubling?
10. Do you use what you have learned in mathematics classes in other classes or in your everyday life? Give an example.
11. What is an equation? How can you use one in physics?
12. How do you take a physics problem and convert it to mathematics?
13. How do you decide which equation to use in a particular problem?
14. What are the steps you use in solving a physics problem? / How do you go about solving a problem?
15. When you have obtained an answer to a problem, what do you do next? Is this different for solving an exam problem vs. a homework problem?
16. When you have solved a physics problem do you have an intuitive feel for the correctness of your answer or do you need to look it up in the back of the book?
17. Do you find derivations done either in the text or in the lecture to be useful? Do you ever do any yourself?
18. Is showing that something is true in math different from the way you would show something is true in physics?
19. When you do an experiment in physics class and you don't get the expected results, what have you shown?
20. Do you feel that the physics you learn in class is connected to the real world?
21. Do you ever find it useful to think about your own experiences and things that you've seen and things that you've done when you're trying to learn physics either in class or when you're studying physics on your own?

These interviews were conducted in three parts: background, survey items, and class comments. If there was sufficient time, a student was asked to work a problem individually as a think aloud. The two-rock problem interview, discussed later in this chapter, was the one most commonly used, particularly at the end of the first term. In the background section, I ask the students about where they grew up, the math and science classes they took previously, and some general expectation questions such as "What did you expect this class to be like?" and "Will learning physics be useful to you in your career?"

For the part of the interview on the survey items, I selected 15-30 of the MPEX survey items to go over with the student(s). In the first two years of the study, I asked the students to read the item aloud, mark their response, and then tell me their response and why they answered that way. When the student finished explaining their response, I would ask a follow-up question if their reasoning was not clear or if they did not give an example. When we were finished with that item, I would tell the students which item I wanted them to discuss next.

This format worked well, but because the students were going through the items one at a time there was a possibility that the discussion of the earlier survey items in the interview could be affecting the students' response and discussion of the latter items. The protocol was changed so that students filled out a special version of the MPEX survey form with room for comments before the interview. I still had the students discuss their responses to selected survey items one at a time, but this allowed me to see which student responses were being changed during the interview and to ask why they were being changed.

In the last part of the interview, I asked the students questions about the class. These included question like “Which activities were most helpful for helping you learn physics?” and “What would you do to improve the course?” I concluded this protocol by asking the students if they had any additional comments about the class or on what they had learned.

The validation results from interviews using this protocol are discussed in chapter 5. An analysis of expectation interviews with students is discussed in chapter 10.

B. Open MPEX Protocol

The open MPEX protocol is shown in Table 7-3. This protocol was designed to look at issues related to the MPEX survey with a heavy emphasis on math expectations and the connections between math and physics. Some of the questions used in this protocol are follow-up questions for the MPEX survey protocol. This protocol was developed to ask questions that would not be as leading to the students as the survey items. The open format with its more open-ended questions tended to produce student responses that were less directed and less focused than the MPEX survey interviews.

Because the this format only addresses some of the issues brought up by the MPEX survey, results from these interviews are discussed in only limited detail in chapter 10. A more detailed analysis of these interviews will be continued after the completion of this dissertation.

III. CONCEPTS

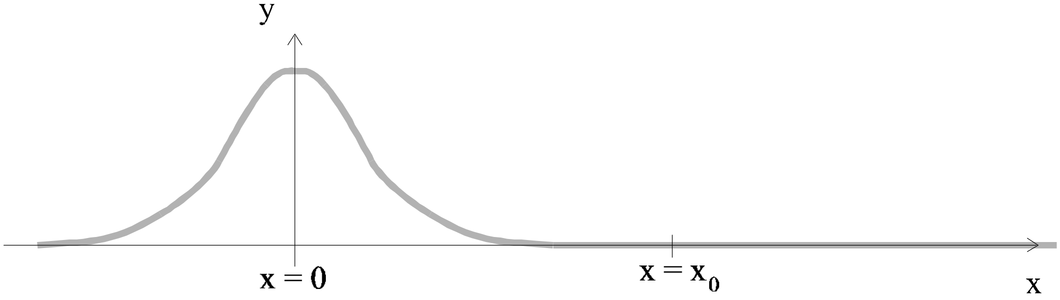
While the MPEX interview protocols use the question and answer technique, both demonstration and problem interviews use the think aloud technique to probe how students think about physics. The two interview studies discussed in this section each play a role in interpreting the study results presented in chapters 9 and 10. The first interview study, the waves-math interview, is a good example of a demonstration interview. It also illustrates an important effect of the fragmentation of student knowledge discussed in chapter 2; namely, that students can simultaneously hold conflicting views and their response to a question may depend on the specific trigger. The second interview, the two-rock problem interview, was used during site visits at three of the ten schools participating in this study as part of the evaluation of both students' conceptual understanding and expectations. Because of students' difficulty with the two-rock problem and the interview focus on issues of conceptual understanding and expectations, the interview protocol calls for more interaction from the interviewer than is usually the case for a problem solving interview both to help the students and to clarify what the student is doing and why.

A. Waves-Math Demonstration Interview

From the 1996 spring semester to the 1997 spring semester, Michael Wittmann[3] and I conducted interviews with the waves-math think-aloud protocol shown in Table 7-4. We designed this protocol to investigate an unusual result from the part one of the pretest shown in Figure 7-1 (a description of pretests and how they are used may be found in chapter 6). The students were shown the shape of a single propagating pulse

Figure 7-1. Waves-Math Pretest from the 1996 Spring Semester

1. Consider a pulse propagating along a long taught string in the +x-direction. The diagram below shows the shape of the pulse at t=0. Suppose the displacement of the string at various values of x is given by $y(x) = Ae^{-\left(\frac{x}{a}\right)^2}$.



   A. On the diagram above, sketch the shape of the string after it has traveled a distance x_0, where x_0 is shown in the figure.

      For the instant of time that you have sketched, find the displacement of the string as a function of x. Explain how you determined your answer.

   B. Consider a small piece of tape attached to the string at x_0. Describe the motion of the tape during the entire motion of the pulse.

2. The experiment described in question 1 is repeated, except that at t=0, $y(x) = 2Ae^{-\left(\frac{x}{a}\right)^2}$.

   A. Compare the motion of the *pulse* in question 1 with the motion of the pulse in this experiment. Explain.

   B. Compare the motion of the *piece of tape* in question 1 with the motion of the tape in this experiment. Explain your reasoning.

on a long string at time t = 0 and given a Gaussian equation y(x) that described the shape of the wave at that time. Then they were asked to draw the shape of the string after the pulses had traveled a distance x_0. Approximately one third of the students drew a pulse that had the same shape but was definitely smaller. This would be a correct response if a student drew the pulse smaller to account for the dissipation that would be observed in a real pulse. However, most of the students who gave a reason explained that the decreased amplitude was due to exponential decay. Wittmann observed a similar result when the pretest was given the following semester.

We believed that the exponential expression $e^{-(x/b)^2}$ in the equation for y(x, t = 0) triggered the students to automatically sketch a smaller pulse. To test our hypothesis, we interviewed student volunteers from a traditional lecture class that had already covered waves. We found that the students had two different ways to think about what was happening to the pulse, either in terms of physical waves or equations.

The two ways of thinking led to two different answers. If a student answered the question by thinking of the pulse as a wave, they said the pulse shape should remain the same. If a student answered the question in terms of the equation y(x) at t = 0, they said the wave would get smaller because of the negative exponent in the exponential term. Two of the students asked if they should consider the problem in terms of waves or the equation and gave the appropriate answers for each view. Another student (code named Ferno) changed his answer as he thought about the problem as shown on page 7-15.[4] (Italics are used here to represent direct quotes from Ferno. Italics within quotation

Table 7-4a. Waves-Math Interview protocol: This interview is designed to look at the consistency of the students' use of math and physics in looking at the shape and speed of a wave in terms of the equation for the wave and the manner in which the wave is created

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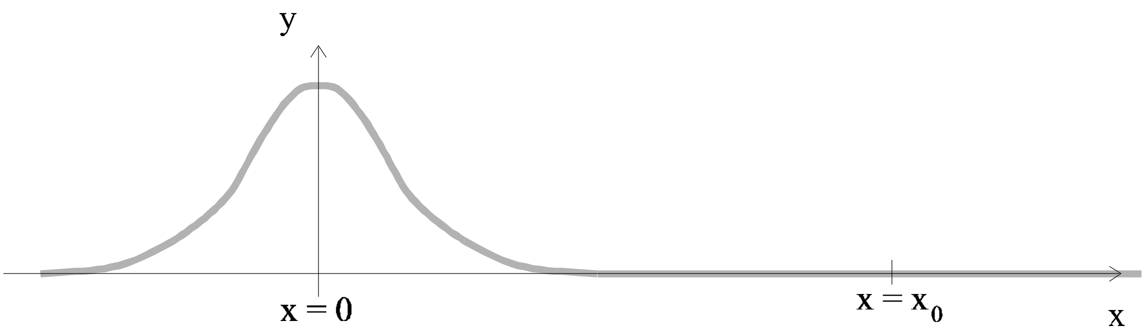
PART I.

STUDENTS ARE GIVEN THE FOLLOWING ON A SEPARATE SHEET:

Consider a pulse propagating along a long taught string in the +x-direction. The string is lying on a table, and there is no friction between the string and the table. The diagram below shows the shape of the pulse at t = 0 s. Suppose the displacement of the string at various values of x is given by $y(x) = Ae^{-\left(\frac{x}{b}\right)^2}$.



ASK THE FOLLOWING QUESTIONS:

- On the diagram you are given, sketch the shape of the string after the pulse has traveled a distance x_0.
- Explain why you drew the string in the shape you did. (How do you account for the shape that you have drawn?)
- Write an equation that describes the displacement of the string after the pulse has moved a distance x_0.
- For the instant you have sketched, write an equation that describes the displacement of the string for all x and all t.
- Imagine you are holding a string attached to a distant wall. How would you create a shape like this on a string?
- Imagine that it takes the pulse 1 second to move from x = 0 to $x = x_0$. How would you shorten this time? (possible follow-up: how would you increase this time?)

Table 7-4b. Waves-Math Interview Protocol cont.

PART II.

A BLANK GRAPH IS GIVEN TO THE STUDENTS. ASK THE FOLLOWING QUESTIONS:

The previous experiment is repeated, except that now you move your hand twice as far to the side in the same amount of time as before.

ASK THE FOLLOWING QUESTIONS:

- Sketch the shape of the string at t = 0? (how is this shape different from the shape of the string in the previous experiment?)
- Could you write an equation for the shape of the string at time t = 0 sec?
- How would the motion of the pulse in this situation compare to the motion of the pulse in the previous experiment?
- Could you sketch the shape of the string at t = 1 sec?
- Write an equation that describes the displacement of the string for all x and all t.

marks indicate Ferno is reading from the interview form.)

> FERNO: [Reading the question]"*... A on the diagram above, sketch the shape of the spring after the pulse has traveled a distance X, zero* [x_0], *where X, zero is shown in the figure. Explain why you sketched the shape as you did*."
>
> *Okay. Umm ...Let's see. "Sketch the shape of the spring after the pulse has traveled"* (MUMBLING AS HE REREADS THE PROBLEM). *... Okay. Over a long, taut spring, the friction or the loss of energy should not be significant; so the wave should be pretty much the exact, same height, distance -- everything. So, it should be about the same wave. If I could draw it the same. So, it's got the same height, just at a different X value.*
>
> *No, wait. Okay. "... the displacement of* (MORE MUMBLING, QUICK READING) *... is given by" -- B, I guess, is a constant; so -- It doesn't say that Y varies with time, but it does say it varies with X. So -- That was my first intuition--but, then, looking at the function of Y ... Let's see, that -- It's actually going to be -- I guess it'll be a lot smaller than the wave I drew, because the first time -- X is zero, which means A must be equal to whatever that value is; because E raised to the zero's going to be 1. So, that's what A is equal to. And then as X increases, this value, E raised to the negative, is going to get bigger as we go up. So, kind of depending on what V is ... Okay. So, if X keeps on getting bigger, E raised to the negative of that is going to keep on getting smaller. So the -- So the actual function's going to be a lot smaller. So, it should be about the same length, just a lot shorter in length.*

Ferno began by thinking of the pulse as a wave in the second paragraph, then he begins to think about the equation y(x, t = 0), and then changed his answer because he saw that y was going to get smaller as x gets bigger. When asked what the equation describes, he replies,

> FERNO: *The equation is just exactly what it says. It's telling you the displacement of the spring, which is going to be in the Y direction. As you pick your X value, that's going to determine your Y value. So, that equation just -- You pick your XO* [x_0] *value, wherever it may be; and that's going to dictate where your Y is going to be.*

From the way Ferno and some of the other students explained what the equation described, it seems that the smaller pulse response is not an automatic response to the sight of the decaying exponential term but instead is due to students thinking that y(x) represents the maximum displacement of the pulse, the amplitude, as a function of position rather than describing the shape of the pulse at time t = 0. The following semester I tested this hypothesis by using the same protocol with two more student volunteers, but the equation describing the pulse was changed to $y(x) = \frac{A}{\left(x/b\right)^2 + 1}$. One of the students used a wave description and said the pulse would retain the its shape and stay the same size. The second student initially answered that the pulse would get smaller because y was getting smaller as x got larger. Then recognizing that A would be maximum displacement or amplitude, she became confused until she realized that the displacement y was not the same as the amplitude A. While trying to resolve y and the amplitude, she clearly indicated that she had thought y described the amplitude of the pulse as a function of the position of the pulse peak.

In summary, by using the pretest results, Wittmann and I were able to design an interview protocol to investigate a student difficulty and understand the student reasoning behind it. From the interview results, we reached the following conclusions:

1. Students are misinterpreting the meaning of the equation and assume a special significance for the pulse peak.
2. Students answer the question differently depending on whether they use their knowledge of waves or their understanding of the equation. Some students hold both perspectives and give both answers simultaneously.

Note that while the first result is consistent with other observations of student difficulties with waves and mathematics, it was only possible to see this connection by using the interviews to see what the students were thinking.[5] Likewise, the second result would likely be unobtainable without the information from the interview. Here we have a direct indication of the fragmentation of student knowledge discussed in chapter 2 and indications of how it is triggered. The two students who held both views simultaneously were aware of the contradiction, but made no effort to resolve it. This issue of simultaneous conflicting concepts and triggering will be needed in interpreting the study results in chapters 9 and 10.

B. Two Rock Problem Interview

The two-rock problem interview is useful for looking at several aspects of student learning including conceptual understanding and expectations. For this reason Hammer used this problem in his interviews with students as part of his dissertation research on cognitive beliefs described in chapter 2.[6] He found it particularly useful for looking at students understanding of the equation $v(t) = v_0 + at$. The problem itself is stated below:

> TWO ROCK PROBLEM: Two rocks are thrown with a speed of v_0 from a cliff of height h. One is thrown horizontally and the other straight down. Which one hits the ground first and which one hits with greater speed?

Although it does not look intimidating to students, many of them find this problem very difficult. One reason is that the wording suggests to them that the problem can be solved easily with the kinematics equations. But without using numbers, students cannot easily compare the times of flights or the final speeds using only the kinematic equations. They are forced to either make up numbers to substitute into the kinematic equations or use their creativity and knowledge to find another way to solve the problem. This can lead to discussions of what the students knows about several of the basic topics in mechanics including the kinematic equations, vectors and vector components, forces, and conservation of energy as well as why the students believe what they know. Hammer used this problem to get students to explain where they thought the equation $v = v_0 + at$ came from, how they knew it was true, and how they might explain it to someone else. He chose to use this problem for his dissertation study because he found Liza and Ellen's interview solutions (in the preliminary study discussed in chapter 2) to the two-rock problem were indicative of their different expectations for the class.

Based on Hammer's work, I decided to use this problem as a follow-up question in many of the MPEX survey interviews to see how the students approached a non-trivial physics problem and to study their knowledge of physics and reasoning in the context of a mechanics problem. The protocol is shown in Table 7-5. This protocol is less detailed than the others described in this chapter because of the more open problem format. The interviewer needs to tailor the questions based on how the student chooses to solve the problem. The questions are guided by the need to clarify the students' approach, their conceptual understanding, and their expectations. One interesting observation from using this protocol is that if the students do not choose to make up and substitute values for the problem, they will usually get stuck. What they do when they get stuck often demonstrates the accessibility and extent of their physics knowledge.

Table 7-5. Two-Rock Problem protocol: This problem was used by Hammer[7] in his dissertation research discussed in chapter 2.

Explain what a think aloud interview is and go over the handout with the student.

> TWO ROCK PROBLEM: Two rocks are thrown with a speed of v_0 from a cliff of height h. One is thrown horizontally and the other straight down. Which one hits the ground first and which one hits with greater speed?

Give the above problem to the students and ask the student to read the problem aloud. Then ask the student what he thinks the answers are to the two parts of the problem and why. After the student has answered, then ask the student to demonstrate that their answer is correct by writing a solution on paper or on the board.

Questions

Which questions are asked depends on how the student goes about solving the problem. Ask questions that clarify how the student is thinking about the concepts and equations that are being used in the solution. The questions asked during the interviews include:

- What is the difference between speed and velocity?
- Are work and energy vectors?
- Is that the velocity vector or a component of the velocity?
- What does conservation of energy mean and how is useful?
- Where do the kinematic equations come from? Can you derive them?

[Some students may be uncomfortable working with symbolic equations. Student may substitute numbers in their solution at any point, but they should be asked how their answers would change if one of the numbers was doubled or halved.]

Interview continues until the student solves the problem or the interviewer calls time.

The two-rock problem protocol is an interesting interview task because it is simple to visualize yet difficult to solve for the students and involves many areas of mechanics. Since I am interested in more than just the student's problem solving skills, this protocol combines features from both demonstration- and problem-style interviews to study conceptual understand and expectations. The results from this protocol are discussed in chapters 9 & 10.

IV. LIMITATIONS

As stated in the beginning of the chapter, interviews are the most effective tool for studying students thinking and reasoning. In interviews one can observe and probe individual students to understand what they are doing and why they are doing it. As we saw in the case of the waves-math study, interviews can provide researchers and instructors with the deeper understanding of what students are doing that is needed to correctly interpret the results of surveys, diagnostics, quizzes, and exams.

However, interviews also have limitations as a research tool. Since this method of evaluation requires extensive resources (mainly time) to conduct, transcribe, and analyze interviews, this method is typically limited to only a small sample (< 10) of students from a given class. This means that means that research studies, that rely solely on interviews, cannot determine how prevalent their findings are for a given class; although, since many of the students share the same difficulties and look at physics in similar ways, a reasonable sample of students will usually give a range of interview responses that are representative of a class.

Another limitation is that interviews are more likely than the other PER assessment methods to cause measurement effects. That is, the interview may cause the subjects to reflect on what they did or even to learn new things. This may lead to changes in the way the subjects learn, think, or reason with regard to physics. This is not usually a problem for single interview, but can be a problem when the interview subjects are interviewed more than once. The interviews can also influence how the subjects respond to class-wide measures such as quizzes, exams, surveys, and diagnostics. One needs to be aware of these potential problems when using interviews in conjunction with other methods of assessment. Effects of this nature can be minimized by restricting the protocol to activities similar to what the subjects already do either in class or on their own.

Another consideration for interviews is the sample of students who participate in interviews. Ideally, one would like a random sample whose views are representative of the class. For most of the interviews conducted as part of this study, we recruited students by just asking for volunteers in class. There is a tendency with this method to recruit the better students from a class because they are more likely to volunteer. In the most recent site visits I have asked instructors specifically to recruit students from the top third, middle third, and bottom third of the class based on their judgment. This provides a more representative student sample. The sample size is also an important factor in determining how representative it is. In this study, sample size varied from 5 to 10 students depending on class size and the availability of the students.

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[1] B. Inhelder and J. Piaget, *The Growth of Logical Thinking from Childhood to Adolescence* (Basic Books, 1958).

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[2] D.N. Perkins, *The Mind's Best Work* (Harvard U. P., Cambridge, MA 1981).

[3] Michael Wittmann is another senior graduate student in the Physics Education Research Group at the University of Maryland. His dissertation research is on students' conceptual and mathematical understanding of waves. He expects to defend in summer 1998.

[4] It should be noted that Ferno was one of the few students who was able to work through and answer the rest of the protocol questions correctly

[5] R.N. Steinberg, M.C. Wittmann, and E.F. Redish, "Mathematical tutorials in introductory physics," in *The Changing Role of the Physics Department: Proceedings of the International Conference on Undergraduate Physics Education*, edited by E.F. Redish and J.S. Rigden (American Institute of Physics, Woodbury, NY 1997), 1075-1092.

[6] D. Hammer, *Defying common sense: Epistemological beliefs in introductory physics*, Ph.D. Dissertation, University of California at Berkeley, 1991 (unpublished).

[7] See Ref. 6.