**Chapter 3: Background, Methods, and Context**

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## Physics Education Research Background

This chapter will provide the reader with a summary of some of the general methods used by physics education researchers to evaluate student understanding. In this dissertation we apply these methods in specific ways to develop a better understanding of the coherence of student content knowledge. This chapter also describes the context of the research.

## Methods of Physics Education Research

Physics education researchers use a number of different methods to probe student understanding. These methods include interviews, multiple-choice questions, and open-ended exam problems. This dissertation uses all of these methods, but most of our data comes from written responses on open-ended exam problems. In this section we provide a brief summary of these general methods followed by a more detailed description of the specific ways the methods were employed in this dissertation.

### Interviews

Interviews provide the most in-depth probe into student understanding. In an interview one or more students will be present with a researcher. The researcher will often have a protocol that may include a specific physics problem, or may include a series of questions concerning a demonstration. The type of interview will depend on the type of study being conducted. During the interview the researcher will try to ask questions that probe existing student understanding, rather than questions that guide students to an improved understanding.

The interview method gives the researcher the ability to probe deeply into student understanding. The researcher can follow up student responses that are unclear with questions designed to elicit clearer explanations. In addition, questions can be constructed on the spot based on interactions with the students. Statements and questions made by the interviewer are also a limitation of the interview method because the question (or measurement) affects the student answer (or observation). Even carefully constructed questions, which try not to guide the students, will affect the student response.

The interviews that were conducted for this work involved students from both the introductory engineering physics course (6 students) as well as advanced students (6 students) studying physics at the University of Maryland. All interviews discussed in this work were done on a one-on-one basis with volunteers and involved students solving problems. Much of the previous work done in understanding student problem solving involves this type of interview. The students were first given a brief introduction to the interview method where they were informed about the anonymous nature of the interview and were told that they should state everything they were thinking out loud. The situation is a bit unnatural for the students. Other researchers have done interviews with two or more students, creating a more natural setting.[1] In the one-on-one interview it was occasionally necessary to remind the students to state what they were thinking and writing out loud. The interviews I conducted typically lasted forty minutes to one hour. After the interview, students were given the opportunity to discuss any aspect of the physics course they wanted. Except for the interviews conducted with the advanced students, all interview questions were based on the material students were currently learning in the course. Because of this, the post-interview discussion often focused on understanding the correct solution to the problem given in the interview. Asking questions that were relevant to the course material also provided motivation for students to participate in the interviews. After the interviews were conducted, most were transcribed and analyzed. Complete transcripts are provided in Appendix C and D for the interviews that are used in this dissertation.

Interviews are usually conducted with a small sample of students because of the amount of time involved in conducting and transcribing interviews. The sample of students that were interviewed was obtained by asking for volunteers in the physics course. A list of the students who were willing to participate in the research was created. A number of students were contacted, at random, from the list, and a time for each interview was arranged. Because participation in this type of study is voluntary, the students who volunteer are not a random sample. Most of the students whose interviews are presented in this work had grades ranging from C's to A's.

### Multiple-Choice Questions and Diagnostics

Multiple-choice diagnostics have become an increasingly popular tool to evaluate student performance. They are the easiest type of measurement device to implement. Because of this, researchers are able to obtain large sample sizes and are also able to conduct statistical analyses on the results. Despite their ease in implementation, data from multiple choice questions are difficult to interpret. There is still debate about what these tests actually measure and a danger that instructors will view the results from these questions in a casual and simplistic manner. [2]

One of the most popular diagnostics used is the Force Concept Inventory (FCI), which was designed by D. Hestenes, M. Wells, and G. Swackhammer and was published in the *Physics Teacher* in 1992.[3] The success of the FCI in drawing out student misconceptions is due to its careful construction and validation. Before the FCI was constructed, the authors performed in-depth studies on the nature of student difficulties in mechanics and collected the results of a large body of published work. The FCI is one of the products of this work. The precursor to the FCI was the Mechanics Diagnostic Test (1985), which was validated through the use of interviews and statistical methods. Because of the similarity between the two instruments, Hestenes et al. did not follow the same procedures to evaluate the validity of the FCI, although they did perform interviews with 20 high school students and 16 graduate students about their answers on the FCI.[4]

According to the Hestenes et al, the FCI "assesses a student's overall grasp of the Newtonian concept of force … [and it] can be used for both instructional and research purposes."[5] The questions on the FCI all deal with mechanics concepts and they are phrased in terms of real world contexts. Because of its construction the FCI can be used both before and after physics instruction. After administering the FCI to their students, most instructors are surprised at their students' poor performance. Because of this, the FCI provided a wake-up call for many instructors. Despite satisfactory performance on exam problems and homework sets, the FCI showed that many students exhibited basic conceptual difficulties in mechanics.

The success of the FCI has prompted the development of other diagnostic tools to evaluate student understanding. Thornton and Sokoloff have developed another mechanics diagnostic called the Force Motion Concept Evaluation (FMCE).[6] Because most of the work conducted in PER is conducted in mechanics, The FCI and FMCE are the most popular diagnostic tools used by instructors and researchers. But there are a number of newer tools being developed to evaluate student understanding of other topics in physics. Diagnostics now exist to evaluate student understanding of waves[7] and student understanding of concepts in electricity and magnetism.[8]

Despite the growing popularity of these instruments there are few studies documenting how student performance on diagnostics correspond with other measures of student understanding. We find that, because student knowledge is often only locally coherent, the context of a problem becomes an important factor in the way students will respond to a question. In this dissertation we will use multiple-choice and corresponding open-ended questions to probe for coherence in student understanding of physics.

### Open Ended Questions and Problems

Questions that ask for detailed written responses are the primary research tool used in this dissertation. These open-ended questions include quantitative questions, qualitative questions, and questions that combine the two. The *quantitative physics problem* is the type of problem at the end of the chapter in introductory physics texts. These problems usually require that the students find the appropriate formula or formulas, manipulate the formulas to fit a given situation, identify the givens and unknowns, and solve for one or more numerical values. Often, little conceptual understanding is required for these problems. These traditional problems are often included on homework assignments and exams in the introductory physics course. A second type of open-ended question is the qualitative question. The *qualitative question* is not as common in the calculus-based course, although it has become a major tool for physics education researchers to use in evaluating student understanding and many texts now include them at the end of the chapters. Qualitative questions usually involve little or no symbolic manipulation or formulas. They require the students to draw upon their qualitative resources and reasoning ability. A third type of question is a *hybrid* or *bridging problem*. These questions require the students to draw upon both their qualitative knowledge and their quantitative knowledge. This may be done by explicitly breaking the problem into qualitative and quantitative parts. It may also be done by designing questions for students to solve that require conceptual understanding. These questions will often require the students to either show all their work or to explain their reasoning. By doing this we are able to get a deeper understanding of what our students are doing. Each type of question serves different purposes for the researcher and instructor.

In this dissertation, quantitative problems that require students to use their conceptual understanding will be used. Sometimes the students are given a problem and simply asked for a certain unknown while other times they are asked a series of qualitative questions before the final quantitative question. These types of questions allow us to look explicitly at student qualitative knowledge, student quantitative knowledge, and the links between them. Comparisons are sometimes made between students who solved identical quantitative questions with and without qualitative parts. Students' solutions can then be compared and the use of qualitative knowledge in solving problems can be evaluated.

### Summary of Research Methods

Each of these three methods has advantages and disadvantages. The main limitation of the interview is the small sample size. To show the distribution of responses, physics education researchers can turn to multiple choice questions and open-ended questions.

Multiple-choice tests are the easiest tool to implement but they are difficult to interpret. This does not imply that multiple-choice tests are not worthy of attention. They provide us with many interesting results about student understanding; but these results may be very different than results on other measures.

Open-ended exam problems are a middle ground between multiple-choice questions and interviews. They can provide the researcher with fairly large sample sizes, and provide the researcher with more information about student reasoning than a multiple-choice question. Due to the nature of this study, open-ended questions were used as the basis of most of the work. Interviews were conducted to probe more deeply into student understanding after open-ended questions were administered.

### Error Analysis

Estimates of the standard error are included in some of the studies in this dissertation. Occasionally we present analyses that compare two quantities. For instance we compare the performance of two different populations in chapter 5 and chapter 8. In order to make claims about our results it is therefore necessary to estimate the error in our measurements.

Error is calculated by making the crude assumption that student responses approximate a binomial distribution. Using this simplified model gives a rough approximation of the uncertainty in our measurements. We use $\sigma^2 = E(x^2) - [E(x)]^2$ and the fact that the expectation value for a binomial distribution is $E(X) = \sum_{r=0}^{N} \frac{N!}{(r-1)!(N-r)!} p^r q^{N-r}$ where $p$ is the probability of the response we are interested in, $q$ *(= 1 – p)* is the probability of a different response, and $N$ is the total number of students in the study. The standard deviation is therefore given by

$\sigma = \sqrt{Npq}$ and the deviation in the percentage of a particular response is $\sigma_P = \sqrt{pq/N}$.
Since most of the data in this dissertation is reported in terms of the percentages, $\sigma_P$ will be used to calculate most of the error in our measurements.

## Context of the Research

### Undergraduate engineering students

Most of the work presented in this dissertation was conducted in the engineering physics sequence at the University of Maryland. The course is a three-semester calculus-based course. The first semester of the sequence (Physics 161) covers mechanics. The second semester (Physics 262) covers the topics of heat and temperature, thermodynamics, mechanical waves, electric fields and electric circuits. The third semester (Physics 263) covers the topics of magnetism, electromagnetic waves, geometric and physical optics, and modern physics. In the second and third semesters students must also enroll in Physics 262A and Physics 263A, the respective laboratory courses. Students do not receive a separate grade for the laboratory. Instead the grade is incorporated into the overall grade for the course. Approximately 200 - 300 students are enrolled in each part of the sequence and these students are divided among two to three lecture classes, each taught by a different instructor.

Each part of the three part sequence consists of three hours a week of lecture and fifty minutes of either a traditional TA-led problem solving recitation or a tutorial section. In the tutorial section the students participate in research-based curriculum emphasizing qualitative understanding.

Students are usually not told whether the class has tutorial sections or traditional recitation sections when they register for the course. Because of this, the populations enrolled in the class with recitations and the population enrolled in a class using tutorials are nearly identical. The PERG at the University of Maryland runs the tutorial part of the class. Because of limited resources, only one or two courses in the sequence will be engaged in tutorials each semester. For instance, in one semester there may be tutorials in both the physics 161 course and the physics 263 course, but the 262 course may have traditional recitations. During most semesters, all the day sections of a particular course will be engaged exclusively in a tutorial curriculum or exclusively a traditional recitation curriculum. Because of logistic reasons the night class at UMd usually has recitations. Students who start in a tutorial class in Physics 161 will usually have tutorials in the physics 262 and 263 courses as well (provided they take them in sequence with no breaks.) Likewise, students who begin with the recitation class will usually have traditional recitations for the remainder of the sequence.

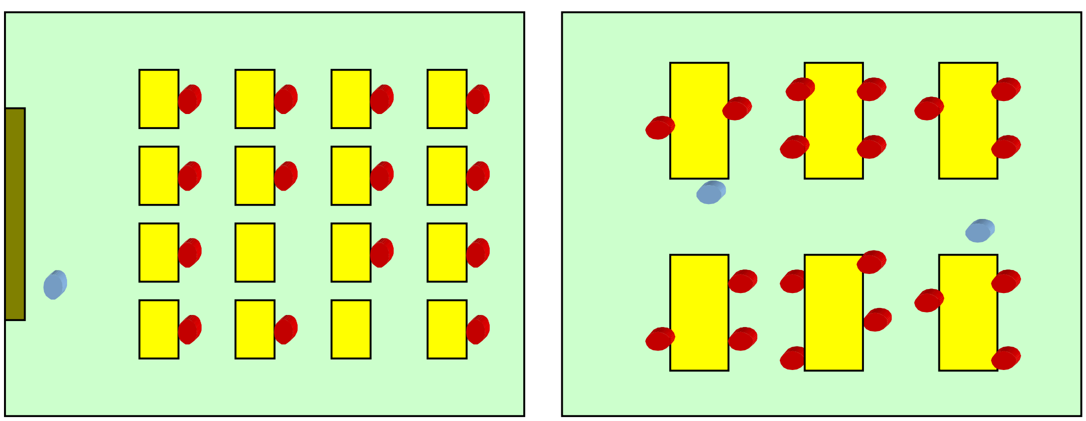
We will use the following terminology to differentiate between the different components of the engineering sequence consisting of Physics 161, 262, and 263. A particular part of the sequence will be referred to as a *course*. Within the course, different lectures are referred to as *classes* and within the classes discussion (tutorial or recitation) will be referred to as *sections*. Therefore a student may be in the engineering sequence, in the Physics 161 course, in the class taught by Dr. X, in the discussion section that meets Wednesday morning.

In a traditional recitation section students typically watch a TA demonstrate how to solve problems at the board. Students often do not actively participate in recitation. Occasionally a TA will introduce innovative instruction in the recitation such as group work, but this not common.

In the tutorial section, students work through researched-based curriculum materials designed by the University of Washington[9] and the University of Maryland physics education groups. Their design is based on extensive research into the student understanding of various topics. Tutorials use conceptual worksheets that promote active learning. Students work in groups of three or four and mostly interact with the other members of their groups. Two facilitators (TAs) go around and ask the students guided questions to help the students construct the understanding for themselves. A schematic of the tutorial section and the recitation section is shown in Figure 3 - 1.

There are a number of important implementation details associated with the tutorial curriculum. These details will be discussed in chronological order to give the reader a clear picture of how the tutorials run in the introductory course. The major components of the tutorial curriculum are pretests, TA training sessions, tutorial sections, tutorial homeworks, and tutorial exam questions. Pretests, TA training sessions, tutorial sections, and tutorial homework assignments all occur once a week. Exam questions occur three to four times during the semester. The following paragraph will describe an ideal implementation of the curriculum. Because of different circumstances, implementation of the tutorials is not always ideal.

The first aspect of the tutorial curriculum are pretests. These one to two page activities are given in the first 10 minutes of the lecture after the material has been lectured on, but before students have gone through tutorial instruction on the material. Students receive credit for participating in the pretests but do not get graded on their responses or get them back. No solutions are posted to the pretests, although the same



(a) (b)

**Figure 3 - 1**

*Schematic showing a traditional recitation class (a) and a tutorial class (b).*

issues are dealt with in the tutorial section where the students are given feedback. Pretests serve two main purposes; they help the students determine what aspects of the material they are having difficulty with after lecture on the material and give them a chance to commit to an answer on their own before the tutorial; they also give the TAs for the class a chance to become familiar with the student difficulties. In addition, the pretests help students identify certain topics as important.

During the TA training sessions the TAs are put in the same role as the students. They first take the same pretest the students took earlier in the week and go over their responses. They then look through and discuss their students' pretests. TAs are therefore made aware of the difficulties some of the students are having with the material that is to be covered in the upcoming tutorial section. By understanding the student errors and difficulties, the TAs are in a better position to address difficulties and questions that will come up in the tutorial sections.

After looking over the pretests and discussing the student responses with the other TAs, the TAs start the actual tutorial. Going through the tutorial serves two purposes. TAs must become familiar with the material in the tutorial if they are to ask the students guided questions on the material. The skill of asking questions that guide the students and allow them to construct the knowledge for themselves is often very difficult to acquire since most of the TAs have learned the material by having explanations given to them.[10] Many TAs therefore want to teach the students in the same way they have been taught. Unfortunately this method is not effective for the vast majority of our introductory physics students.[11] The second purpose of the meeting is to give the TA's the opportunity to confront and resolve any difficulties they, themselves, may have with the material.

Tutorial sections last fifty minutes and are given once a week, just like the TA-led problem solving recitations. Students enter the class and begin working on the conceptual worksheets once their group is assembled. The tutorial worksheets either come from the *Tutorials in Introductory Physics*[12] book or are given to the students as handouts. Students mainly interact with their group members. Two TAs are in the tutorial room at once, asking students guided questions about the tutorial material. Students keep the tutorial worksheets to help them with the tutorial homework assignments and to help them study for the exams. Attendance is not required in the tutorial sections, although attendance is typically quite good. Attendance in the tutorial section during the period of this study was approximately 80%. Besides getting a better understanding of the material, incentive for coming to tutorial comes from the graded tutorial homework assignments and the graded exam question based on one of the tutorials.

Tutorial homework is assigned each week in addition to the textbook homework assignments given by the instructor for the class. Because of the additional tutorial homework, there are fewer problems assigned from the textbook. Tutorial homework is based on the tutorial the students have just completed and is due the following week. The tutorial homework assignments are graded and returned to the students.

Most of the incentive for attending the tutorial session probably comes from the tutorial exam question. Students are told at the beginning of the semester that one question on each exam is based on the tutorial. If students do not attend the tutorial sections the exam question will be very difficult for them; if they attend and work diligently through the tutorials they usually perform well on the exam question.

In order to help students form coherence in their qualitative and quantitative knowledge the UMd PERG has begun designing instructional material to help students make connections between the concepts they develop in tutorial and quantitative problem solving. *Problem Solving Tutorials* and *Bridging problems* are implemented on a small scale to help the students make this bridge.

Problem-solving tutorials occur either once or twice a semester. They are implemented in the same way other tutorials are implemented, but instead of having students construct an understanding of a particular topic or topics, they include applications of the concepts developed in earlier tutorials in the context of three to four carefully constructed problems. These problems consist of both qualitative parts and quantitative parts to help the students develop more coherence between the concepts and quantitative problem-solving.

Bridging problems are sometimes given as part of the tutorial homework assignments. They are supplements to the more conceptual part of the tutorial homework assignments and are based on the tutorials the students have just completed. Like the problems given in the problem-solving tutorials, the bridging problems contain both qualitative and quantitative questions designed to help the students make the link between these two types of knowledge.

### Advanced Students

In addition to the undergraduate engineering majors a small number of studies were conducted with advanced physics students. These students volunteered for interviews on topics in mechanics and physical optics. Two students were second-year graduate students, three were first-year graduate students, and one student was an upper-level undergraduate student who was enrolled in a number of graduate courses. All students were physics majors at the University of Maryland.

## Summary of the Data

The data that is presented in this dissertation comes from the many different physics topics that span the three semesters of the engineering sequence at the University of Maryland (UMd). One reason for the wide range of topics is to show that the difficulties students have in making the connections between their qualitative and quantitative knowledge and making connections across physics topics and concepts is not topic dependant. It also shows the pervasiveness of this fragmentation in physics knowledge.

Table 3 - 1 summarizes the data that is presented in the dissertation. It contains a brief description (name) of the question, the format of the class, the format of the question, the date of the study, and the location in the dissertation where the data are first presented.

| Description of Problem (name) | Format of Class | Format of question | Date Administered | Location in dissertation |
|---|---|---|---|---|
| NI, NII, and motion diag. | Phys 161, w/ tutorial | Open-ended exam prob. | Spring 1996 | Chapter 4 |
| NIII-carts | Phys 161, w/ tutorial | Open-ended exam prob. | Fall 1995 | Chapter 4 |
| Force Concept Inventory | Phys 161, w/ tutorial | MC questions. | Fall 1995, Spring 1996 | Chapter 4 |
| Hand-block | Graduate Students | Prob. Solving Interview | Fall 98 | Chapter 5 |
| Hand-block | Phys 161, w/ recitation | Open-ended quiz prob. | Fall 97 | Chapter 5 |
| Tension-block | Phys 161, w/ tutorial | Open-ended bridging prob. | Spring 97 | Chapter 5 |
| Tension-block | Phys 161, w/ tutorial | Prob. Solving Interview | Spring 97 | Chapter 5 |
| Thermo-piston | Phys 262, w/ tutorial | Open-ended pretest | Fall 97 | Chapter 5 |
| Inductive Circuits | Phys 263, w/ tutorial | Open-ended exam prob. | Spring 99 | Chapter 6 |
| Momentum Question | Phys 161, w/ recitation | Open-ended exam prob. | Fall 97 | Chapter 6 |
| Resistive Circuit | Phys 262 | Open-ended exam prob. | Fall 97 | Chapter 6 |
| Electric Fields and Potential | Phys 262, w/ tutorial | Open-ended bridging prob. | Fall 97 | Chapter 6 |
| Physical Optics I | Phys 263, w/ tutorial | Open-ended exam prob. | Spring 96 | Chapter 6 |
| Tension-Two Blocks | Phys 161, w/ tutorial | Open-ended exam prob. | Fall 98 | Chapter 7 |
| Heat Transfer | Phys 262 | Open-ended exam prob. | Spring 96 | Chapter 8 |
| Physical Optics II | Phys 262 | Open-ended exam prob. | Spring 96 | Chapter 8 |

**Table 3 - 1**

*Table showing a summary of each question(s) discussed in the dissertation.*

[1] This method is used in B. Sherin, "The Symbolic Basis of Physical Intuition: A study of two symbol systems in physics instruction," Ph.D. dissertation, School of Education, University of California, Berkley, (1996).

[2] For a discussion on how to interpret multiple-choice tests see R. S. Steinberg and M. S. Sabella, "Performance on multiple-choice diagnostics and complimentary exam problems," Phys. Teach. **35** (3), 150-155 (1997) and D. Huffman and P. Heller, "What does the Force Concept Inventory actually measure?" Phys. Teach. **33**, 138-143 (1995), D. Hestenes and I. Halloun, "Interpreting the force concept inventory, a response to the March 1995 critique by Huffman and Heller," Phys. Teach. **33**, 502 (1995), and P. Heller and D. Huffman, "Interpreting the force concept inventory, a reply to Hestenes and Halloun," Phys. Teach. **33**, 503 (1995).

[3] D. Hestenes, M. Wells and, G. Swackhammer, "Force Concept Inventory," Phys. Teach. **30** (3) 141-153 (1992).

[4] For more information on the FCI see ref. 3 and J. M. Saul, "Beyond Problem Solving: Evaluating introductory physics courses through the hidden curriculum," Ph.D. dissertation, Department of Physics, University of Maryland, College Park, (1998).

[5] See Ref. 3.

[6] R. K. Thornton and D. R. Sokoloff, "Assessing student learning of Newton's laws: The Force and motion concept evaluation and the evaluation of active learning laboratory and lecture," A. J. Phys. **66** (4) 338-351 (1998).

[7] M. C. Wittmann, "Making Sense of how students come to an understanding of physics: An example from mechanical waves," Ph.D. dissertation, Department of Physics, University of Maryland, College Park, (1998).

[8] Private communications with R. Thornton, D. Sokoloff and D. Maloney, T. Okuma, C. Heiggelke

[9] L. C. McDermott, P. S. Shaffer, and the PEG, *Tutorials in introductory Physics*, (Prentice Hall, NY, 1997).

[10] Most physics majors will spend time outside of class to reason out the information themselves. Unfortunately, most of our service course students do not do this.

[11] Redish states that physicists as a group seem to be selected for the character of being able to learn on their own in E. F. Redish, "Millikan Award Lecture (1998): Building a Science of Teaching Physics," Am. J. Phys. **67** (7), 562-573 (1999).

[12] See Ref. 9.