Chapter 1: Physics Education: the Physics of Education in Education of Physics

Introduction

Physics Education Research (PER) has been growing rapidly for the past two decades and is becoming a major field of research in physics. The results from this research have already made a strong impact on the ways that many instructors teach physics. The major objective of PER is to understand the difficulties that students often encounter in learning physics and then find ways to help the students. As a systematic research, PER often involves the following elements:

- theoretical development on theories to model the learning process especially the conceptual learning that takes place in the context of learning physics,
- detailed investigations of student difficulties in learning specific topics of physics,
- the development of probing instruments that can provide reliable and effective measurement on the various aspects of student understanding of physics,
- the development and implementation of new instructional strategies that can provide students with a more effect learning environment,
- the development of evaluation tools and methods that can do effective processing of the data to provide accurate and comprehensive assessments of student understandings.

Currently in PER, a lot of research has been done on the investigation of specific student difficulties in various contexts and on the development of new instructions to help students with these difficulties. On the other hand, there hasn't been much research on developing a consistent theory and methodology that can be used to model the student learning processes in a variety contexts of physics. Without the guidance of a coherent theoretical framework, individual researchers often carry out their studies with their own unique ways making the results highly context dependent. Although this situation can often bring the community many new interesting ideas, but it can often result in certain difficulties for people to compare results from different experiments and to understand each other's research. The problem is partially eased when a few standardized probing instruments become available, e.g., the Force Concept Inventory (FCI) and the Force Motion Concept Evaluation (FMCE).[1, 2] A lot of research has been conducted based on the two tests.

As more multiple-choice instruments are being developed and implemented, the limitations of this type of instrument are getting more concerned. That is, the traditional ways of evaluating the data of multiple-choice tests (in the form of scores) often fail to provide the information on student actual understandings of the related topics. Sometimes, a score can even give misleading results. For example, in certain situations, students with all sorts of incorrect understandings of the concept of Newton's Third Law can come up with the same correct answer to a question (see chapter 5 for details).

Therefore, it is urgent and important to develop a general theory and methodology to model students' understanding of physics and to develop effective numerical methods to do quantitative evaluation of detailed progress of student learning. With the theoretical guidance and mathematical tools, we can develop more effective assessment instruments to facilitate our research and instruction.

Overview of the Dissertation

This dissertation is about the research on developing a theoretical and mathematical framework to model the student learning process and to do quantitative evaluations of student understandings of physics. The dissertation has two parts. Part I, chapters 2-5, gives a detailed discussion of the new theory and mathematical tools to study the student learning. Part II, chapters 6-8, gives an example of a systematic investigation on student difficulties in learning quantum mechanics based on the methods developed in Part I. The following is a brief introduction of all the chapters.

In chapter 2, I give an introduction on the theoretical elements, e.g., the definition of "student model" and "model space", which are used to represent and study the dynamics of student modeling. I will also introduce a mathematical representation, which is used for developing mathematical algorithms to do quantitative analysis of student models.

In chapters 3 and 4, I discuss the details of two algorithms developed to do quantitative evaluations of student models with data from multiple-choice questions. These two algorithms form the basis of the model-based analysis method, which is called *Model Analysis*. The first algorithm is the concentration factor, which produces a numerical measure – the concentration factor. It, on one hand, can provide useful information on student model condition and can be used as a tool to identify or verify possible common student models from the data. On the other hand, the concentration factor also tells about the quality of the test questions (see chapter 3 for details). The second algorithm is the model state evaluation, which analyzes the relation of student responses and extracts the detailed structural information of student models. In both algorithms, the complete student responses on a multiple-choice test are used (not just the scores). With properly designed instruments, the results can tell about not only what the student difficulties are but also the possible causes of their problems.

In chapter 5, I discuss additional algorithms to deal with multiple-choice multiple-response questions and questions with "coupled" responses, i.e., one response can be the results of a student applying two or more different models. A number of new measurements on the different features of probing instruments are also introduced. Specific examples with Wave Test and FMCE test will be discussed in detail.[3] In addition, I will also introduce a new development on modeling student model structures and model evolution processes with physical features of the contexts. This chapter also includes a summary of implications on model-based instrument design.

Chapter 6 starts the second part of the dissertation. It gives an introduction to the research on student difficulties in learning quantum mechanics. This research is conducted based on the theory developed in Part I. Therefore, emphasis is made on the study of the incorrect student models underlying the many types of student difficulties. The major objective for this research is to identify the various student models, which will be use in our further development of instruments appropriate to use with Model Analysis algorithms and new instructions to help students.

In chapter 7, I give a detailed discussion on the research on student difficulties with classical issues that are pre-requisites of quantum mechanics. Two specific topics are studied in detail, student understanding of potential energy diagram and student understanding of classical probability. Common incorrect student models are identified and new instructions are developed to help students with their difficulties. The effects of the new instructions are also discussed.

Chapter 8 discusses the study of student models of real quantum concepts such as wavefunction and quantum probability. Based on the results from research, a multiple-choice instrument is also developed. The questions are used in the final exam in an upper division quantum class at University of Maryland (UMd). Student models on both the quantum barrier and quantum probability are evaluated and discussed. I will also introduce the new instruction developed to help students understand these difficult quantum concepts.

The dissertation concludes with chapter 9, which gives a brief summary of the Model Analysis tool and speculations on methods for evaluation of student models.

Research Context

In the first part of the dissertation, examples with student data on FCI and FMCE test are studied. The data was collected from three schools, University of Maryland (UMd), Prince George Community College (PGCC at Maryland), and California Polytechnology Institute (CalP).[4, 5] All classes are first-year calculus-based introductory physics classes (mechanics).

There are three different types of instructions including traditional lectures, University of Washington (UW) style *Tutorials*, and *Real Time Physics* (RTP).[6, 7] Classes in UMd and PGCC are using either traditional lectures or tutorials. Classes in CalP are using either traditional lectures or RTP.[8]

The traditional instruction has three one-hour lectures and a one-hour recitation session each week. The tutorial-based instruction is semi-traditional. It also has three one-hour lectures each week. However, instead of doing the recitation session, a one-hour tutorial is used each week. The tutorials are interactive group learning sessions usually with hands-on labs and computer-based tools. In the tutorial sessions, students work in groups of three or four students, and answer questions on a worksheet that guides them to build correct qualitative reasoning on a physics concept. Teaching assistants serve as facilitators, asking leading questions to help the students construct understandings with their own reasoning.

RealTime Physics consists of coherent series of laboratory modules based on *Tools for Scientific Thinking* and *Workshop Physics*. These modules are conceptual hands-on laboratory activities and microcomputer-based laboratories (MBL). The course is activity-based where lectures are replaced by activities enabled by MBL and other computer tools.[9,10]

The second part of the dissertation discusses the research on student understanding of quantum mechanics. For this part of research, two UMd classes are studied, Phys263 and Phys420. Phys263 is the third (last) course of the calculus-based introductory physics series at UMd. In the classes studied, we spent four weeks to make an introductory to quantum mechanics. The instruction was based on quantum tutorials.

The Phys420 is an upper-division undergraduate quantum mechanics class designed for engineering majors. The students are mostly seniors and about 60% of them are electrical engineering (EE) majors. I have done detailed study of classes with two different environments. The two classes in fall 97 and fall 98 are traditional style with three hours of lectures per week. The spring 98 and spring 99 classes use tutorial-based curriculum with two hours of lectures and one hour of tutorial each week.

References and Endnotes:

[1] D. Hestenes, M. Wells, and G. Swackhammer, "Force Concept Inventory", *The Physics Teacher*, Vol (**30**), 141-153, 1992.

[2] Developed by R.K. Thornton and D. Sokoloff. Related reference: R. K. Thornton, "Conceptual Dynamics: Changing Student Views of Force and Motion," Proceedings of the International Conference on *Thinking Science for Teaching: the Case of Physics.* Rome, Sept.1994.

[3] The Wave Test was developed by Michael Wittmann at the University of Maryland. For details please see chapter 5. Reference: M. Wittmann, "Making sense of how students come to an understanding of physics: An example from mechanical waves", Ph.D. dissertation, University of Maryland, 1998.

[4] Data collected by Dr. Jeff Saul at the University of Maryland (UMd) and the Prince George Community College (PGCC).

[5] CalP student data is collected by Hadley Lawler, a former PER graduate student at UMd.

[6] L. C. McDermott, P.S. Shatter, *Tutorials in Introductory Physics* (Prentice Hall, New York, 1998)

[7] See reference 2.

[8] R. K. Thornton, "Conceptual Dynamics: Changing Student Views of Force and Motion," Proceedings of the International Conference on *Thinking Science for Teaching: the Case of Physics.* Rome, Sept. 1994

[9] P. Laws, "Calculus-based physics without lectures", Phys. Today **44**, 24-31 (Dec., 1991)

[10] R.K., Thornton, "Tools for scientific thinking – microcomputer-based laboratories for teaching physics", Phys. Ed. **22**, 230-238 (1987)