PART I. INTRODUCTION AND BACKGROUND: PHYSICS EDUCATION RESEARCH, STUDENT LEARNING AND ASSESSMENT

Chapter 1. Introduction

Physics Education Research (PER) has led to the development of a large number of innovative instructional approaches to address student difficulties with traditional instruction. Yet, as a community, we are only beginning to determine how to evaluate these curricula appropriately. There are currently few widely accepted methods for determining if these improved curricula are more effective than traditional instruction in helping students reach a broad range of course goals. This dissertation examines the effectiveness of traditional instruction and three research-based curricula. It will also examine the methods used to evaluate effectiveness. The three research-based curricula are University of Washington *Tutorials*,[1] University of Minnesota *Group Problem Solving & Problem Solving Labs*,[2] and Dickinson College *Workshop Physics*.[3]

I. MOTIVATION

Over the last twenty years, PER has changed our view of student learning in the traditional introductory course. The main findings of PER can be summarized in the following three points:

1. Traditional instruction is not working for many students in the introductory physics course.[4]
2. Students are not "blank slates." Students' experiences and cognitive attitudes can affect what they learn in an introductory course. Many student experiences and beliefs are not compatible with what we want them to learn, hinder students' learning of physics, and outlast instruction.[5]

3. Research-based curricula can be developed to improve student learning by helping students change their common sense conceptual beliefs through active engagement.[6]

These new research-based curricula often require additional resources and changes in teaching style in order to be implemented effectively. The cost of change has caused many instructors to ponder if it is worth the effort. This question is difficult to answer unless we can determine if these new curricula help students learn more effectively than traditional instruction, particularly in institutions adopting curricula developed at other institutions. Thus, there is a great need to carefully examine how to evaluate the effectiveness of a new curriculum in terms of student learning. Before this issue can be discussed further, we need to consider what are appropriate course goals.

II. COURSE GOALS AND THE HIDDEN CURRICULUM

The first step in evaluating the success of any curriculum is to examine the goals of the course. The main goal in most traditional physics classes is for the students to demonstrate mastery of the course material through typical end-of-chapter problems on course assignments and exams. However, most physics instructors have goals for their students that go beyond this. These additional goals are often neither stated explicitly to the students in class nor reinforced through grading and testing. We refer to this kind of learning goal – a goal not listed in the course syllabus or in the textbook – as part of the courses' "hidden curriculum."[7] Many students who are considered successful in traditional lecture classes are often unsuccessful with these additional learning goals.[8] For example, many students who have mastered the main goal of solving end of chapter problems:

- have a weak grasp of basic physics concepts,

- are unable to apply what they know to new situations,
- believe that physics is just a collection of equations and procedures that deal with very specific situations,
- do not believe that physics has anything to do with their everyday life, and
- do not see physics as a process of trying to make sense out of the physical world.

Examples of these difficulties will be cited in chapter 2 and/or documented from detailed observations throughout this dissertation.

The model of student learning used in this dissertation is a growth model rather than a knowledge-transfer model.[9] This model focuses on what is happening to the student trying to learn rather than on what the teacher is doing. Based on this model and the results stated above, the main goal of an introductory physics course, even for non-majors, should be to help students build a good functional understanding of physics that they can use to solve problems in new contexts, i.e. to become more like expert problem solvers. This requires students to develop multiple skills including the following:

- to be able to understand and use the underlying physics concepts,
- to know when and where specific concepts apply,
- to be able to express their functional understanding in multiple representations including graphs, equations, and words, and
- to understand the nature of physics and how to use it effectively in and out of class.

Traditional exam problems and multiple-choice concept tests can help assess what is happening in some of these goals, but not all. As we see in chapter 2 in the examples of Mazur, Hammer, Tobias, and others, what traditional assessments tell us about student learning is often unclear. What is needed is to develop an assessment strategy that determines a more complete picture of these learning outcomes and what they tell us about teaching effectiveness.

In developing such a strategy, we need to keep in mind that we do not expect students to become expert problem solvers as the result of one introductory physics sequence. However, we can determine elements, i.e. skills and qualities, that are on the path to the development of expert problem solving, scientific reasoning, and a scientific viewpoint. Once we identify and select the elements we want to study, then we can determine how to assess these elements to see if progress is being made.

III. PROBLEM STATEMENT/RESEARCH QUESTIONS

This dissertation discusses assessment issues, evaluates assessment techniques, and applies these techniques to evaluate the effects on student learning of three PER-based curricula compared with traditional instruction. Because PER-based curricula are fairly new and because so little has been done with evaluation in terms of the hidden curriculum, there are many issues to consider concerning course evaluation. To limit the scope of this dissertation, I focus on two aspects of student learning from the hidden curriculum: (1) conceptual understanding of physics and (2) student "expectations."

1. *Conceptual understanding of physics*: Successful students should develop both a good understanding of physics concepts and the ability to use that understanding to solve physics problems. This includes the ability to use conceptual understanding in solving new and complex problems. This aspect is discussed in more detail in chapters 2, 4, 6, and 9.
2. *Expectations*: By "expectations" I mean the attitudes and beliefs students have about the nature of learning, physics, and mathematics. Studies by Hammer and Schoenfeld (discussed in Chapter 2) have shown that expectations can have a significant effect on how students learn and what they get out of a course. In particular, if the students' expectations are different from the instructors, it can distort what the students get out of the class. This is discussed in more detail in chapters 2, 5, and 10.

The dissertation focuses on the following three questions:

1) What are the characteristics of different student populations coming into the calculus-based introductory physics class?
2) How do we determine if students are improving their knowledge of physics concepts and expectations?
3) Are the research-based curricula more effective for teaching students to improve their conceptual understanding and their expectations of physics?

IV. EXPERIMENTAL DESIGN

This dissertation evaluates both the methods used to determine what students learn and what these methods tell us about students' learning. These methods include observations, survey instruments, interviews, and exams. The strengths and weaknesses of each method are discussed with examples. The two main survey instruments used are the Force Concept Inventory (FCI)[10] and the Maryland Physics Expectation (MPEX) survey.[11] The FCI is used to measure gains in students' understanding of basic physics concepts while the MPEX survey is used to study student expectations. The development of the FCI by Hestenes *et al*. is discussed in chapter 4. The development of the MPEX survey by Redish, Steinberg, and the author is discussed in depth in chapter 5.

To determine the effect of instruction, the students were evaluated with concept tests and the MPEX survey at the beginning and end of the first quarter or semester of the introductory physics sequence. The MPEX survey was also given at the end of the first year of instruction.

Most students in service courses only see introductory physics topics from a physicist's viewpoint once. Because of this and the increasing importance for physics departments to document learning outcomes for these classes, we have limited our study to introductory sequences that were designed primarily for non-physics majors. For this dissertation, I selected the calculus-based introductory sequence. This sequence is particularly interesting for studying how students view the role of mathematics in physics since students in calculus-based physics courses should be expected to have a reasonably strong math background and to develop a mathematical understanding of introductory physics.

The students participating in this study were taught with one of four curricula which vary in the amount of active-learning activities used in class:

1. The traditional lecture method uses almost no active learning activities in lecture or recitation and its associated laboratories tend to be over structured (cookbook).
2. The University of Washington's tutorial curriculum is a modification of the traditional lecture course that substitutes cooperative-group concept-building activities for the recitations but does not change the lecture part of the course.
3. In the University of Minnesota's Group Problem Solving & Problem Solving Laboratory approach, the structure of the course is the same as the traditional lecture method, but the lecture, recitation, and laboratory are all modified into a more coherent course. The lecture emphasizes major themes and models a prescribed problem-solving strategy. Working in cooperative groups, the students use the prescribed problem-solving strategy to solve story problems and laboratory problems in recitation and laboratory, respectively.
4. *Workshop Physics* is a no lecture/all guided-discovery laboratory course developed at Dickinson College. This curriculum consists almost entirely of cooperative group active-learning activities and makes heavy use of microcomputer-based laboratory (MBL) tools for data acquisition and modeling.

The four curricula were studied at implementations at ten colleges and university across the United States. The ten schools either were asked to participate in this project because of the teaching methods used in the introductory course or asked Redish or the author to participate in the project to increase their awareness of student learning in the hidden curriculum. The implementations include both primary implementations, implementing curricula developed by that institution, and secondary implementations, in which institutions adopt curricula developed at other institutions. A detailed description of both the curricula and the implementations is given in chapter 8. I conducted interviews with students during site visits to five of the ten schools. Note that not all types of data were collected at all ten schools.

V. DISSERTATION OVERVIEW

This dissertation is divided into the four parts:

Part I. Introduction and Background:
Physics Education Research, Student Learning, and Assessment

Part II. Research Methods and Assessments:
How Do We Determine What Students are Learning?

Part III. Evaluation of Research-based Teaching Methods

Part IV. Conclusion

Part I is an introduction to the dissertation and provides the reader with background information on what is known from PER on student learning in physics including the following: problem solving, conceptual understanding, students' cognitive beliefs or expectations and their implications for physics instruction (chapter 2), and an overview of the research methods and models used in PER (chapter 3). In Part II, I describe in detail the research methods used in this dissertation and I discuss the reliability, validity, limitations, and what is learned from each method. The research methods include: multiple choice concept tests (chapter 4), the Maryland Physics Expectations (MPEX) survey (chapter 5), specially constructed conceptual quizzes and exam problems (chapter 6), and interviews with students at five of the ten schools (chapter 7). Part III contains a description of the three types of research-based instruction and traditional instruction including details on the implementations at each of the ten schools (chapter 8), assessment of students' conceptual understanding (chapter

9), and assessment of students' expectations (chapter 10). Part IV contains the conclusion which summarizes the dissertation results, discusses the implications for instruction and curricula improvement, and suggests directions for future study.

VI. DISSERTATION SUMMARY

In this dissertation, I am evaluating student learning with respect to conceptual understanding and expectations (cognitive or epistemological beliefs) in classes using either one of three PER-based curricula or traditional lecture instruction. The classes participating in this study were calculus-based introductory physics classes at ten undergraduate institutions including a community college, five small liberal arts colleges, and three large state universities. For this study, I collected four types of assessment data to study students' expectations and students' conceptual understanding: multiple choice concept test (mainly FCI) data, MPEX survey data, student interviews, and qualitative exam problems. The FCI is a nationally recognized tests of students' conceptual understanding of mechanics.[12] The MPEX survey is a new instrument to study student expectations developed specifically for this study in collaboration with Richard N. Steinberg and Edward F. Redish. The survey results are evaluated in terms of the overall result and six sub-scores or dimensions of expectation including:

- the role of the student in learning physics – *independence,*
- the structure of physics knowledge – *coherence*,
- understanding physics equations vs. just using them – *concepts*,
- the connection between physics and everyday life – *reality link*, and
- the connection between mathematics and physical situations – *math link*.

Over one hundred hours of interviews were conducted with students at five of the participating institutions. Two specially designed exam problems were used in the introductory sequence at University of Maryland to look at students' application of conceptual knowledge on final exams.

The results that I present in this dissertation will show the following five points:

1. There are significant differences among the different student populations participating in the study as they come into the introductory course with regards to both students' conceptual understanding and expectations.

Concepts: The three large state universities and Drury College had initial average FCI scores of approximately 50%. The three other private liberal art schools had significantly lower FCI scores at the beginning of the semester. Their initial FCI average scores range from an average of 37.6% at NWU to 43.6% at Dickinson College.

Expectations: The University of Minnesota and Dickinson College classes' initial responses to the survey were significantly more favorable for learning physics than the classes at University of Maryland for three of the six MPEX dimensions measured: independence, reality, and effort. (In this dissertation, significant changes refer to statistically significant differences.) Nebraska Wesleyan University and Drury College classes' initial expectations were statistically significantly more favorable overall and in two or more MPEX dimensions than classes at Maryland, Ohio State University, Moorhead State University, and Prince Georges Community College. In addition, students at Skidmore College and Ohio State had significantly more favorable reality link expectations initially than students at Maryland.

2. The three research-based curricula are more effective than traditional instruction in helping students learn key concepts.[13]

The figure of merit of basic conceptual understanding of key concepts in this dissertation is the fraction of the possible gain[14] achieved by the class from matched[15] pre- to post-test scores on the FCI.[16] In this study, the traditional lecture classes at University of Maryland had an average FCI fractional gain of 0.19±0.03. Courses using one of the three research based curriculum had average FCI fractional gains of 0.35±0.01 to 0.46 ±0.03. These results are consistent with the results of a previous 6000 student study by Hake of pre and post FCI scores from traditional and research-based instruction (see chapter 5).[17] In addition, the classes using research-based curricula had significantly better gains on Newton's third law questions on the FCI, often found to be one of the hardest concepts in introductory mechanics. At Maryland, the classes using tutorials also did significantly better than traditional lecture classes in responding to multiple choice velocity graph questions.

3. For all classes participating in this study, overall student expectations as measured by the MPEX survey deteriorated at least slightly after one year of instruction, regardless of the curriculum. However, the four Workshop Physics courses and the Maryland sequence with two semesters of Tutorials did not have significant unfavorable shifts in overall expectations.

For the MPEX survey, shifts in student expectations are measured by comparing pre- and post-sequence matched student responses. A shift in student responses for a given sequence $\geq 2\sigma$ is considered to be significant.[18] The overall MPEX responses from students in introductory sequences after one year of traditional instruction and or one year of the Group Problem Solving curriculum became significantly more unfavorable for learning physics over the year. Recall that unlike the other research-based curricula, the emphasis of the Group Problem Solving curriculum is on problem solving, not conceptual understanding.

4. The MPEX responses from Dickinson College, where the Workshop Physics curriculum was developed and the Tutorial sequences at Maryland both improved significantly in one dimension, student expectations towards conceptual understanding.

The Workshop Physics sequences at Dickinson College where it was developed and Tutorial sequences with two semesters of Tutorials both had significant increases in the number of favorable responses to the survey on the items in the concept dimension. It should be noted that the other Workshop Physics classes were either in their first or second year of implementation. Dickinson College had been using Workshop Physics for several years before their participation in this study. Surprisingly, only the Group Problem Solving sequence at Minnesota showed a significant decrease in this dimension.

5. For all four curricula, student expectations deteriorated over the year in terms of connecting physics to the real world. Two of the Workshop Physics sequences, both Group Problem solving sequences, and the traditional sequence at Minnesota deteriorated in student expectations on linking mathematics to physical situations.

The only sequences where student responses did not become more unfavorable with regards to the link between physics and the students' everyday experiences was the Workshop Physics class at Drury College. The decrease in favorable responses was significant for the sequences taught with traditional instruction and Group Problem Solving as well as the Workshop Physics sequence at Moorhead State University. In addition, responses from half the sequences studied including the Workshop Physics sequences at Nebraska Wesleyan and at Moorhead State and the sequences at Ohio State and Minnesota regarding the connection between math and the system under study became significantly more unfavorable.

6. The mechanics exam problem and the interviews indicate that many students are having difficulty applying mechanics concepts to open-ended qualitative problems. The two harmonic oscillator problems indicate that many

> Maryland students have trouble connecting concepts and graphs to physical situations in problems. After completing a modified tutorial, the students showed significant improvement on a similar problem.

The Tutorial students did significantly better than the students who had traditional recitations on the qualitative mechanics exam problem shown in Figure 6-2 in drawing a velocity graph and ranking forces for the accelerating two-cart system . However, the number of correct student responses was less than might be expected from the post FCI results. This discrepancy suggests that while the multiple choice questions provide an indication of students' conceptual knowledge, a good score on a test like the FCI may overestimate students' ability to use their conceptual knowledge on more open-ended qualitative problems.

The two harmonic oscillator problems (Figures 9-9 & 9-10) require students to qualitatively graph the displacement vs. time curves for two spring-mass systems released at rest at t = 0 on the same axis. On the first harmonic oscillator final exam problem, approximately one-quarter of the students drew graphs that showed the correct basic features of the two curves including starting at maximum displacement. After changes were made to the tutorial, approximately three quarters of the tutorial students drew curves that had the correct basic features.

Using the combined research methods of surveys, non-traditional problems, and interviews to study student learning in classes using research-based and traditional lecture instruction, this dissertation provides new insights into students' conceptual understanding and the role of expectations in learning physics. This is the first wide-scale study of the implementation of Tutorial, Group Problem Solving, and Workshop Physics curricula that includes secondary implementations, i.e. schools that adopt a curriculum instead of developing their own. The results of this study will help give researchers and instructors a better understanding of the issues in the hidden curriculum for consideration in curriculum design and/or implementation in the calculus-based introductory physics sequence.

---

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

[2] P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," *Am. J. Phys.* **60**, 627-636 (1992); P. Heller and M. Hollabaugh, "Teaching problem solving through cooperative grouping. Part 2: Designing problems and structuring groups," *Am. J. Phys.* **60**, 637-644 (1992); P. Heller, T. Foster, and K. Heller, "Cooperative group problem solving laboratories for introductory courses," 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), 913-934.

[3] P.W. Laws, *Workshop Physics Activity Guide* (Wiley, New York NY, 1997).

[4] I. A. Halloun and D. Hestenes, "The initial knowledge state of students," *Am. J. Phys*. **53** (11), 1043-1055 (1985); R. K. Thornton and D. R. Sokoloff, "Learning motion concepts using real-time microcomputer-based laboratory tools," *Am. J. Phys*. **58** (9), 858-867 (1990); L.C. McDermott, "Millikan Lecture 1990: What we teach and what is learned — Closing the gap," *Am. J. Phys*. **59** (4), 301-315 (1991); A. van Heuvelen, "Learning to think like a physicist: A review of research based instructional strategies," *Am. J. Phys.* **59**, 898-907 (1991); D. Hestenes, M. Wells, and G. Swackhamer, "Force concept inventory," *Phys. Teach.* **30**, 141-158 (1992); P.S. Shaffer, *Research as a Guide for Improving Instruction in Introductory Physics*, Ph.D. Dissertation, University of Washington, 1993 (unpublished); E. Mazur, *Peer Instruction: A Users Manual*, (Prentice Hall, New Jersey, 1997).

[5] L. Viennot, "Spontaneous reasoning in elementary dynamics," *Eur. J. Sci. Educ*. **1**, 205-221 (1979); D.E. Trowbridge and L.C. McDermott, "Investigation of student understanding of the concept of velocity in one dimension," *Am. J. Phys*. **48**, 1020-1028 (1980); D.E. Trowbridge and L.C. McDermott, "Investigation of student understanding of the concept of acceleration in one dimension," *Am. J. Phys*. **49**, 242-253 (1981); A. Caramaza, M. McCloskey and B. Green, "Naive beliefs in 'sophisticated' subjects: Misconceptions about trajectories of objects," *Cognition* **9**, 117-123 (1981); J. Clement, "Students' preconceptions in introductory mechanics,"

Am. J. Phys. **50** (1) 66-71 (1982). M. McCloskey, "Intuitive physics," *Sci. Am* **249** (4), 122-130 (1983); I. A. Halloun and D. Hestenes, "Common sense concepts about motion," *Am. J. Phys*. **53** (11), 1056-1065 (1985); S. Tobias, *They're Not Dumb, They're Different: Stalking the Second Tier* (Research Corp., Tucson AZ, 1990); D. Hammer, "Epistemological beliefs in introductory physics," *Cognition and Instruction* **12**, 151-183 (1994); D. Hammer, "Students' beliefs about conceptual knowledge in introductory physics," *Int. J Sci*. Ed. **16**, 385-403 (1994).

[6] For example: R. Thornton and D. Sokoloff, *Tools for Scientific Thinking* (Vernier Software, Portland OR, 1992 and 1993); C.W. Camp and J.J. Clement, *Preconceptions in Mechanics: Lessons Dealing with Students' Conceptual Difficulties* (Kendall/Hunt Publishing, Dubuque IA, 1994): L.C. McDermott, *Physics by Inquiry*, 2 Vol. (Wiley, New York NY, 1995); P.W. Laws, *Workshop Physics Activity Guide* (Wiley, New York NY, 1997); L.C. McDermott and P.S. Shaffer, *Tutorials in Introductory Physics* (Prentice Hall, Upper Saddle River NJ, 1997) and Refs. 2 & 3.

[7] E. Silver, "Foundations of cognitive theory and research for mathematics problem solving instruction," in *Cognitive Science in Mathematics*, edited by A. Schoenfeld (Erlbaum, Hillsdale NJ, 1987) 33-60. For earlier use of the term "hidden curriculum," see H. Lin, "Learning physics versus passing courses," *Phys. Teach*. **20**, 151-157 (1982) and the references therein.

[8] See Ref. 4.

[9] E.F. Redish, "Implications of cognitive studies for teaching physics," *Am. J. Phys*. **62** (9), 796-803 (1994).

[10] D. Hestenes, M. Wells, and G. Swackhamer, "Force Concept Inventory," *Phys. Teach*. **30** (3), 141-158 (1992).

[11] E.F. Redish, J.M. Saul, and R.N. Steinberg, "Student expectations in physics," *Am. J. Phys*. **66** (3), 212-224 (1998).

[12] See Ref. 10.

[13] Preliminary data suggests that with research-based instruction, student performance on traditional measures is as good as with traditional instruction and may be better.

[14] The fraction of possible gain h is given by the following equation:
h = (class post-test average – class pre-test average) / (100 – class pre-test average)
This quantity is discussed in more detail in chapter 4.

[15] Here "matched" means that only students who took both the pre-test and the post-test FCI are included in the analysis.

[16] R.R. Hake, "Active engagement vs. traditional methods: A six thousand student study of mechanics test data for introductory physics courses," *Am. J. Phys*. **66** (1), 64-74 (1998).

[17] See Ref. 10.

[18] The standard deviation σ for an MPEX measurement is discussed and defined in chapter 5.