
Making Sense of How Students Come to an Understanding of Physics: An Example from Mechanical Waves



Michael C. Wittmann
Department of Physics
University of Maryland,
College Park MD 20742-4111

*<http://www2.physics.umd.edu/~wittmann/research>
wittmann@physics.umd.edu*

ABSTRACT

While physics education research (PER) has traditionally focused on introductory physics, little work has been done to organize and develop a model of how student come to make sense of the material they learn. By understanding how students build their knowledge of a specific topic, we can develop effective instructional materials. In this dissertation, I describe an investigation of student understanding of mechanical and sound waves, how we organize our findings, and how our results lead to the development of curriculum materials used in the classroom.

The physics of mechanical and sound waves at the introductory level (using the small-amplitude approximation in a dispersionless system) involves fundamental concepts that are difficult for many students. These include: distinguishing between medium properties and boundary conditions, recognizing local phenomena (e.g. superposition) in extended systems, using mathematical functions of two variables, and interpreting and applying the mathematics of waves in a variety of settings. Student understanding of these topics is described in the context of wave propagation, superposition, use of mathematics, and other topics. Investigations were carried out using the common tools of PER, including free response, multiple-choice, multiple-response, and semi-guided individual interview questions.

Student reasoning is described in terms of primitives generally used to simplify reasoning about complicated topics. I introduce a previously undocumented primitive, the object as point primitive. We organize student descriptions of wave physics around the idea of patterns of associations that use common primitive elements of reasoning. We can describe students as if they make an analogy toward Newtonian particle physics. The analogy guides students toward describing a wave as if it were a point particle described by certain unique parts of the wave. A diagnostic test has been developed to probe the dynamics of student reasoning during the course of instruction.

We have replaced traditional recitation instruction with curriculum materials designed to help students come to a more complete and appropriate understanding of wave physics. We find that the research-based instructional materials are more effective than the traditional lecture setting in helping students apply appropriate reasoning elements to the physics of waves.

TABLE OF CONTENTS

List of Tables	v
List of Figures	vii
Chapter 1: THE NEED FOR SYSTEMATIC INVESTIGATION OF STUDENT UNDERSTANDING OF PHYSICS.....	1
Introduction	1
Physics Education Research.....	2
Wave Physics	2
Student Difficulties with Wave Physics	3
Organizing Student Difficulties	3
Designing Curriculum to Address Student Needs.....	4
Investigating the Dynamics of Student Reasoning	4
Chapter 2: REVIEW OF PREVIOUS RESEARCH	6
Introduction	6
Research Methods	6
Common Sense Physics	8
Wave Physics: Basic Concepts.....	12
Deriving the wave equation as a consequence of local interactions	13
Deriving the wave equation for sound waves	14
Physical Meaning of the Wave Equation	16
Local interactions on a global scale.....	16
Solutions of the wave equation as propagating waves	17
Wave velocity depends on medium properties.....	18
Superposition	18
The role of modeling	19
Initial conditions and boundary conditions	20
Previous Research into Student Difficulties with Waves.....	22
Research context and setting of previous research.....	22
Student difficulties with the propagation of waves	24
Propagation on a taut spring or string system.....	24
Sound wave propagation	26
Student difficulties with the mathematical description of waves.....	29
Student difficulties with superposition	31
Research as a Guide to Curriculum Development	32
Summary.....	36
Chapter 3: STUDENT DIFFICULTIES WITH WAVE PHYSICS.....	40
Introduction	40
Research Setting.....	40
Chosen wave representations.....	41

Student Understanding of Wave Propagation: Mechanical Waves	41
Investigating student understanding	42
Discussion of student difficulties	44
Student Understanding of Wave Propagation: Sound Waves	47
Investigating student understanding	47
Discussion of student difficulties	49
Student Understanding of the Mathematics of Waves	54
Investigating student understanding	55
Discussion of student difficulties	56
Student Understanding of Wave Superposition	59
Investigating student understanding	59
Discussion of student difficulties	62
Summary of Specific Student Difficulties with Waves	65
Chapter 4: A PROPOSED MODEL OF STUDENT LEARNING	67
Introduction	67
Reasoning Primitives	67
General Reasoning Primitives	69
Force and Motion Primitives.....	71
Primitives Describing Collisions.....	72
Facets of Knowledge: Context-Specific Interpretation of Primitives.....	73
Parallel Data Processing	75
Patterns of Association, Guiding Analogies, and Mental Models.....	77
Models of Conceptual Change.....	81
Summary.....	83
Chapter 5: THE PARTICLE PULSES PATTERN OF ASSOCIATION.....	87
Introduction	87
Student use of Primitives in Wave Physics	88
The object as point primitive.....	88
Common primitives in wave physics	91
Ford	94
David	96
Kyle	97
Ted	99
Summary of common primitives students use in wave physics.....	100
The Particle Pulses Pattern of Association	101
Chapter 6: DEVELOPMENT, IMPLEMENTATION, AND EVALUATION OF TUTORIALS	105
Introduction	105
Creating Video Materials for Classroom Use	106
Wave Propagation and Wave superposition	111
Description of Tutorial	111
Student Understanding of Wave Propagation.....	113

Student Understanding of Wave Superposition	115
Mathematical Description of Waves.....	116
Description of Tutorial	116
Student Understanding of the Mathematics That Describe Waves	118
Sound Waves	119
Description of Tutorial	119
Student Understanding of Sound Waves	120
Conclusion	122
 Chapter 7: INVESTIGATING THE DYNAMICS OF STUDENT REASONING.....	124
Introduction	124
Preliminary Diagnostic Test.....	124
Final Diagnostic Test.....	129
Pre-Instruction Diagnostic Test, Final Version.....	129
Post-Instruction Diagnostic Test, Final Version	131
Comparison of Student Pre- and Post-Instruction Performance	132
Inconsistent reasoning to describe a single wave physics topic	132
Multiple reasoning methods to describe wave physics	134
Describing class use of different reasoning methods	136
Summary.....	139
 Chapter 8: SUMMARY	141
Introduction	141
Specific Examples of Student Reasoning About Waves.....	142
Organizing Student Responses.....	143
Curriculum Development to Promote Appropriate Student Reasoning	144
Investigating the Dynamics of Student Reasoning	145
Summary.....	146
 Appendix A: PROPAGATION AND SUPERPOSITION OF WAVEPULSES TUTORIAL	148
 Appendix B: THE MATHEMATICAL DESCRIPTION OF WAVEPULSES TUTORIAL	161
 Appendix C: SOUND WAVES TUTORIAL.....	170
 Appendix D: WAVE DIAGNOSTIC TEST	
1. PRELIMINARY VERSION.....	180
2. FINAL VERSION, PRE-INSTRUCTION	189
3. FINAL VERSION, POST-INSTRUCTION	195
 Bibliography.....	198

LIST OF TABLES

Table 2-1	Percentage of correct responses for students sketching a v vs. x graph of an asymmetric wavepulse propagating along a string (see Figure 2-12).	30
Table 3-1	Comparison of student pre-, post-traditional, and post-tutorial instruction responses to the FR and MCMR wave propagation question.	46
Table 3-2	Comparison of student pre- and post-traditional instruction responses describing the motion of a dust particle due to a sound wave.	53
Table 3-3	Student pre-, post-lecture, and post-tutorial descriptions of the effect of a sound wave on a dust particle floating in air.	54
Table 3-4	Student use of functions to describe a propagating Gaussian pulshape.	58
Table 4-1	Primitives as defined by diSessa.	69
Table 4-2	Common facets described by Minstrell that relate to forces exerted by one object on another.	73
Table 4-3	Galili's description of three patterns of association and typical explanations using each in three different settings.	79
Table 5-1	Set of primitives often used by students when reasoning about wave physics.	90
Table 5-2	Specific primitives used by students when reasoning about wave physics.	91
Table 5-3	Newtonian particle physics analogies of the Particle Pulses Pattern of Association and the correct wave physics of the Community Consensus Model.	101
Table 6-1	Comparison of student pre-instruction responses on FR and MCMR wave propagation questions, Fall-1997.	112
Table 6-2	Comparison of student post-instruction (lecture and tutorial) responses on FR and MCMR wave propagation questions, Fall-1997.	112

Table 6-3	Student performance on wave superposition questions at different times during F97.	114
Table 6-4	Performance on student pretest, comparing descriptions of dust particle and candle flame motion.	117
Table 6-5	Comparison of student responses describing the motion of a dust particle due to a loudspeaker, pre- and post-instruction (unmatched).	119
Table 6-6	Student performance on sound wave questions before, after traditional lecture, and after additional modified tutorial instruction.	119
Table 7-1	Table of S97 wave diagnostic questions that were used to determine if students were answering using the PM or CM.	124
Table 7-2	S97 wave diagnostic test responses split by topic.	126
Table 7-3	Summary of statistical data presented in Figure 7-4 and Figure 7-5.	136

LIST OF FIGURES

Figure 2-1	Iterative cycle of research, development, and instruction, centered around an understanding of student models of learning.	6
Figure 2-2	Blocking of spin states in a ferromagnet as an analogy to describe levels of analysis possible in a system.	9
Figure 2-3	The Clement coin toss problem.	10
Figure 2-4	A small amplitude wave propagating along the length of a long, taut string.	13
Figure 2-5	A sound wave propagating through a long air-filled cylinder.	14
Figure 2-6	The interaction between the real world and a theoretical model which describes it and predicts its behavior.	20
Figure 2-7	Comparing wavepulses and wavetrains.	21
Figure 2-8	Maurines question to investigate how students viewed the relationship between the creation of the wave and the motion of the wave through the medium.	24
Figure 2-9	Maurines question to investigate how students interpret damping in a wave system.	25
Figure 2-10	Linder and Erickson question to investigate effect of sound wave on candle flame.	26
Figure 2-11	Students sketch to show how sound propagates.	27
Figure 2-12	Context of Grayson question with a propagating asymmetric wavepulse traveling to the right on a long, taut string.	29
Figure 2-13	Common student difficulty with a v vs. x graph of a string on which a wave is propagating.	30
Figure 2-14	Superposing wavepulses on opposite sides of a long, taut string.	31
Figure 2-15	Atwood's machine and Modified Atwood's machine apparatus.	33

Figure 2-16	Diagram from the UW pretest on the Atwood's machine.	33
Figure 2-17	Examination question asked at UW to investigate student understanding of tension after instruction.	35
Figure 3-1	Wave propagation question, Fall-1995, pre-instruction.	42
Figure 3-2	Free response (FR) and multiple-choice multiple-response (MCMR) versions of the wave propagation question.	43
Figure 3-3	Dust particle and candle flame versions of the sound wave question.	48
Figure 3-4	MCMR format sound wave question.	49
Figure 3-5	Alex's sketch of the sound wave exerting a force on the dust particle.	51
Figure 3-6	Wave-math question.	55
Figure 3-7	Correct and most common incorrect response to the wave-math question.	56
Figure 3-8	Wave superposition question with unequal amplitude pulses on the same side of the string.	61
Figure 3-9	Correct and most common incorrect response to the superposition question in Figure 3-8.	61
Figure 3-10	Wave superposition question with identical shaped pulses on opposite sides of the string.	62
Figure 3-11	Correct and most common incorrect response to the superposition question in Figure 3-10.	62
Figure 3-12	Wave superposition with mirrored asymmetric wavepulses on the same side of the string.	63
Figure 3-13	Correct and most common incorrect responses to the superposition question in Figure 3-12.	63
Figure 4-1	Questions asked to compare student understanding of momentum and kinetic energy.	70
Figure 4-2	The word APPLE and the simple line shapes that can be combined to form all the letters in the word.	75

Figure 4-3	Sketch of the torque balance task.	75
Figure 6-1	Sketch of set-up for creating wavepulses on a stretched snake spring.	104
Figure 6-2	Screen capture of video <i>triangle.mov</i> .	105
Figure 6-3	Screen captures of videos <i>diffamps.mov</i> , <i>diffshape.mov</i> , and <i>diffdens.mov</i> .	107
Figure 6-4	Screen capture of <i>triangle.mov</i> being analyzed in VideoPoint™.	108
Figure 6-5	Comparison of student responses on the MCMR wave propagation question, F97 pre and post-tutorial instruction, S96 post-traditional instruction	113
Figure 7-1	Comparison of post-instruction PM and CM use by 15 tutorial and 5 traditional instruction students on the preliminary wave diagnostic test.	125
Figure 7-2	Histograms of student PM and CM responses on sound wave questions in the final version wave diagnostic test, pre- and post-tutorial instruction.	131
Figure 7-3	Histograms of student PM and CM responses on the final version wave diagnostic test, pre- and post-tutorial instruction.	133
Figure 7-4	Pre- and post-instruction PM use on the wave diagnostic test, data fits.	135
Figure 7-5	Pre- and post-instruction CM use on the wave diagnostic test data fits.	135
Figure 7-6	Finding the best fit of pre-instruction PM data by using a lin-log plot.	136

Chapter 1: The Need for Systematic Investigation of Student Understanding of Physics

Introduction

Investigations of student difficulties with physics are growing in number and sophistication. As researchers gain deeper insight into student understanding of the material taught in the classroom, they are able to create curriculum materials that are more effective in improving a student's actual understanding. At the same time, growing understanding of student reasoning provides the opportunity to find more systematic descriptions of how students come to make sense of the physics. By evaluating student performance in a modified curriculum setting, researchers can then develop an understanding of not only the curriculum's effects on student learning, but also the manner in which a curriculum *can* affect student learning.

There are many goals when investigating student understanding of physics. As researchers, we aim to recognize and “diagnose” specific difficulties while also finding the most common difficulties related to a specific topic. We try to help individual students more effectively while also creating curriculum that helps the highest number of students overcome the most common difficulties. The general goal is to help students understand what it means to understand physics.

In this dissertation, I will discuss the above ideas in the context of student difficulties with the physics of mechanical waves. The physics of mechanical waves is common to most introductory physics curricula at the university level and provides many interesting topics in which to discuss how students come to an understanding of physics. My investigations have taken place at the University of Maryland (UMd) with engineering students taking a required three-semester sequence of physics classes. The students discussed in this dissertation were in the second semester of the sequence.

In this chapter, I summarize the dissertation by giving an overview of the issues that affect the discussion of physics education research on student understanding of mechanical waves. Rather than discussing the contents of each chapter in order of its appearance, I will describe some of the issues that play a role in the dissertation while pointing out where a discussion of these issues can be found.

Physics Education Research

The field of Physics Education Research (PER) has come about in reaction to the growing need for innovative methods in education that address student difficulties with the difficult material they are required to learn in our physics classrooms. PER involves

- investigations of specific aspects of student understanding of the physics,
- the development of investigative probes to help fulfill this goal,
- the development of statistical methods that help researchers organize, analyze, and present their findings,

- the design and implementation of curriculum materials that provide a more effective learning environment for students, and
- evaluations of the effectiveness of these materials.

In chapter 2, I give an overview of PER by summarizing work done by some of the leaders in the field. In the course of the analysis, I discuss different methods of analysis that have been used, including focusing both on specific aspects of understanding only and on broader descriptions of common student difficulties. In addition, I discuss how PER can lead to curriculum materials that can be demonstrated to be effective in addressing student difficulties with the physics. The remainder of the dissertation presents my own work, done as part of the Physics Education Research Group (PERG) at UMd, which involved all the aspects of PER as described above.

Wave Physics

In order to discuss student understanding of wave physics, it is necessary to describe in detail what it is that we want them to actually learn in our classes. A mechanical wave is a propagating disturbance to a system, such as a wave traveling on a long, taut string. At the introductory level, we teach students a very simplified model of waves. In this model, there are no large amplitude waves and there is no dispersion in the system. Any disturbance will propagate indefinitely. Mathematically, these traveling waves can be described by functions of the form $f(x \pm vt)$, where f is any function that describes the displacement of the mechanical wave from equilibrium.

In chapter 2, I discuss the generally accepted model of waves that is taught at the introductory level. Many of the ideas of wave physics are subtle and rarely addressed explicitly in textbooks. For example, an understanding of waves requires an understanding of the role of initial conditions to help create a wave, though the initial conditions do not affect the manner of the wave's propagation through the system. Also, propagation occurs due to local interactions between "nearest neighbors" in the system. Student understanding of the distinctions between local phenomena and global phenomena plays a central role in this dissertation.

After the discussion of the physics, I discuss previous research by summarizing the literature of investigations into student difficulties with wave physics. Very few studies have been published, and the common themes among those that are available suggests that wave physics is a rich topic for investigating more general patterns of reasoning that we find in students.

Student Difficulties with Wave Physics

The wave physics topics discussed in this dissertation include

- wave propagation speed (and how to change it),
- wave superposition (point-by-point addition of displacement),
- the mathematical description of waves (the $f(x \pm vt)$ dependence), and
- the physics of propagating sound waves.

In addition, other topics play a role, such as wave reflection, though these have not been investigated in as great detail.

The specific wave physics topics serve as a context in which to discuss concepts and ideas that are more general to physics as a whole. These general ideas (displacement from equilibrium, for example, or the role of initial conditions in describing the dynamics of a system) build on concepts that students have encountered in their previous mechanics classes and also play a role in students' future studies. As a result, the discussion of student difficulties in chapter 3 provides a context in which to discuss how students build on the knowledge that they bring into the classroom.

Organizing Student Difficulties

In addition to investigating student difficulties with specific physics concepts, we must also try to find ways to organize, explain, and discuss systematically how students are coming to their understanding of the material. An extensive literature has grown in the fields of education and cognitive studies in which these issues are addressed. In chapter 4, I give a summary of some of these ideas that help account for some of the difficulties we see students having with wave physics. Each of the different cognitive concepts that I discuss is presented with a typical example of how student reasoning has been interpreted in physics through the use of these different ideas. By presenting these cognitive ideas, I suggest a model of learning that is applicable to describing student difficulties with waves.

In chapter 5, I apply the proposed model of learning to the specific student difficulties first presented in chapter 3. We describe student reasoning in terms of fundamental and very simple ideas that are consistently and generally applied to many different situations. These *reasoning primitives* are generally applicable to many different situations in many different (possibly non-physics) settings. In physics, the same primitive may be applied in contradictory ways to a single physical situation. We refer to the application of a primitive in a context as a facet of reasoning.

In chapter 5, I discuss a primitive not previously presented in the literature, the *object as point* primitive. Students often apply this and other useful and reasonable primitives (helpful in mechanics, for example) inappropriately when thinking about the topic of wave physics. This provides us with a context in which to discuss different aspects of student reasoning. On the one hand, it is encouraging to see students trying to make sense of new topics in terms of the material that they have learned in previous semesters (though well-researched difficulties from mechanics arise again). On the other hand, we find that students do not have the ability to determine whether the primitives that they apply to a situation are appropriate in that setting.

Furthermore, many students seem to inappropriately use a set of primitives in conjunction with each other. We describe this as a pattern of association, meaning that students seem to use more than one primitive inappropriately to describe a single topic, but we do not claim that this is a robust model that students have in their head. The pattern of association may serve to help guide a student's choice of primitives in a given context. We refer to the pattern of association that many students use when discussing the physics of mechanical waves as the *Particle Pulses Pattern of*

Association, because student responses indicate a simplification of finite length waves to single points (rather than extended regions of displacement). In addition, students show great difficulties reasoning about force and motion with waves.

Designing Curriculum to Address Student Needs

To help students in their learning of physics, we have begun to develop and implement a set of instructional materials that are designed to address specific student difficulties with the material. These materials, known as *tutorials*, are based on a design by the University of Washington (UW) Physics Education Group, under the guidance of Lillian McDermott. In tutorials, students participate in a process in which we

- *elicit* their difficulties, through questions that ask for their predictions or descriptions of a physical situation,
- *confront* students with a weak understanding of the material with evidence to show that their predictions were incorrect, and
- help students *resolve* their difficulties through guided questions and activities designed to let the student build their own robust understanding of the material.

The process of the development of research-based curriculum materials is described in chapter 2 in the context of a UW tutorial. Tutorials developed at UMD to address student difficulties with wave physics are described in chapter 6. This description includes a summary of how the computerized videos used in the instructional materials were created. In addition, in chapter 6 data are presented to indicate how effective the curriculum materials have been in addressing student difficulties. We have compared student performance from the beginning of an instructional sequence (pre-instruction on waves), the middle of the instructional sequence (after lecture instruction, but before tutorial instruction), and the end of instruction (after all instruction in the class has been completed). We find that student performance improves greatly as a result of research-based curriculum materials.

Investigating the Dynamics of Student Reasoning

To better describe how student reasoning about the physics changes over the course of instruction, we have developed a diagnostic test that allows us to gain deeper insight into student reasoning on many different aspects of the physics at once. By using many questions that ask about the same topic, we are able to see the extent to which students reason consistently about the physics. By using the same questions before and after instruction, we are able to compare the development of student reasoning as a result of different instructional materials.

We find that students are not consistent in their reasoning. We can describe two patterns that students use to guide their reasoning: the Particle Pulses Pattern of Association, mentioned above, and the community consensus model of waves. Through the use of a short diagnostic test, we have been able to describe the dynamics of student reasoning as moving from a primarily incorrect application of otherwise useful and reasonable primitives to a state where they use both types of reasoning.

The implications for instruction in physics are that students leave our classes with an incomplete understanding of when to use which reasoning while thinking about the physics. I discuss the dynamics of student reasoning in chapter 7 of this dissertation.