Chapter 8: Summary

Introduction

Our investigations of student understanding of wave physics show that students do not bring so much a body of pre-existing knowledge but a way of applying their pre-existing knowledge to a new and unfamiliar situation. Much of their knowledge is appropriate in some settings but inappropriately applied in others. During our courses, they learn the correct material that we want them to learn, but they still hold on to their previous way of thinking about the physics. In this chapter, I briefly review the results discussed in previous chapters and summarize our findings.

As part of ongoing research by the Physics Education Research Group (PERG) at the University of Maryland (UMd), I have investigated student understanding of some of the introductory physics concepts of waves taught in the engineering physics sequence at UMd. Investigations used the common research methods of physics education research. In-depth understanding of student reasoning was gained through the use of individual demonstration interviews. In this setting, students are probed as thoroughly as possible about an individual topic because the researcher has the ability to follow up on student comments. Interviews form a sort of “state space” of possible responses that can be used to analyze other probes that gives less insight into student reasoning. For example, written tests allow for more students to answer a single question, but the researcher is usually unable to follow up on student responses. In both written tests and interviews, it is possible to ask questions in a variety of formats. In this dissertation, I describe free response and multiple-choice, multiple-response questions in some detail.

The model of waves which students learn in this course consists of small amplitude waves traveling through ideal media such that there was no loss and no dispersion in the system. This model was investigated in the context of mechanical waves (on a taut string or spring) and sound waves (in air). Topics include wave propagation, superposition, and reflection of mechanical waves (on a string) and the propagation of sound waves. For both mechanical and sound waves, I have also investigated the mathematical descriptions students use to describe the medium through which the waves travel. Students have fundamental difficulties with each of these topics, and their reasoning shows that they often are unable to apply fundamental ideas of physics appropriately.

In our physics classrooms, we expect our students to understand and apply well-defined, coherent models of physical systems. The results presented in this dissertation indicate that many students have a fragmented picture of physics. They seem to access their knowledge depending on criteria triggered by the question and situation at hand. Thus, they may simultaneously have both correct and incorrect ideas about specific physical situations. Both as instructors and as physics education researchers, we benefit from an understanding of the elements of students’ reasoning and the criteria by which students organize their understanding.

Specific Examples of Student Reasoning About Waves

The brief examples given below of specific student difficulties with wave physics are described in more detail in chapter 3.

We asked students to describe how they could change the speed of a wavepulse created by a quick flick of a hand holding a long, taut string. Before any instruction, 13% of the students who answered a free response version of this question gave the correct answer that only changes to the medium (its mass density or tension) would have the desired effect. Of the other students, 77% stated that the demonstrator creating the wave would have to move her hand more quickly (or slowly) to create a faster (or slower) wave. Thus, students are unable to separate the propagation of a wave from the initial condition that describes its creation. Instead, students describe the motion of the wave as if it were directly influenced by the manner of the wave's creation.

Student description of the motion of a dust particle floating in air due to a sound wave propagating through the air showed that students are unable to separate the sound wave from the medium through which it travels. Both before and after traditional instruction, more than 40% of the students state that a dust particle in such a situation will be pushed away from the loudspeaker in the direction of wave propagation. (96 students answered the question before instruction and 104 answered after instruction. Data are not matched, in the sense that these are not the same students, but other research results are consistent with these data.) Student explanations indicate that they are thinking of sound as moving air exerting a force (in only the direction of propagation) on the medium through which it travels. After instruction, less than half the students (46% of 104 students) describe the dust particle oscillating due to the sound wave, and only 24% correctly indicate that the motion is longitudinal. Many students are unable to distinguish between a propagating disturbance to a medium and the medium itself. Instead, many students describe the wave as the motion of the medium itself.

When discussing superposition, many students do not always think of a mechanical wave as an extended region that is displaced, but instead describe the wave by a few specific and significant points. For example, when two wavepulses (finite length waves, as opposed to infinitely long, e.g. sinusoidal, wavetrains) coincide but their peaks do not overlap, many students do not show superposition in the appropriate regions. Instead, they state that the wave only superposes when the amplitudes overlap. By "the amplitude," these students mean only the peak amplitude. Before instruction, 65% of 131 students give answers similar to this one, while only 27% show point-by-point addition of displacement at all appropriate locations. Even after traditional instruction, 53% of the students describe superposition in terms of only the amplitude point, and 26% give the correct response. Students giving the amplitude response are not recognizing a wave as a disturbance to the system that covers an extended region. Instead, they use a single point to describe the entire wave and neglect all the other displaced points in their descriptions.

In a fourth area of wave physics, we have investigated student interpretations of the mathematics used to describe waves. Students were given the shape of a Gaussian wavepulse propagating along an ideal, taut string and the equation to describe the shape of the string at time t = 0 s, $y(x) = Ae^{-\left(x/b\right)^2}$. They were then asked to sketch the shape of the spring and write an equation to describe the shape they had sketched after the peak of the wavepulse had moved a distance x_0 from the origin. Of the 57 students, 35% sketched a shape with a smaller amplitude. Though a physically appropriate description (if students were taking into account the loss in the system, which they were told was ideal), the explanations students give indicate that they are instead being guided in their reasoning through a misinterpretation of the mathematics. Many students interpret the variable x to mean the position of the peak of the pulse. The variable y describes the amplitude of the pulse for these students. Thus, when the x value increases (to x_0, for example), the amplitude of the wave decreases. This description is similar to the one given by many students describing superposition. Students do not use the mathematics to describe the entire string. Instead, they focus on the peak of the wave as the important point described by the mathematics.

Organizing Student Responses

The brief description below of how we organize student reasoning is described in more detail in chapter 4, and the interpretation of student results in terms of this approach is described in more detail in chapter 5.

To systematize student reasoning, we have described their reasoning in terms of primitives applied inappropriately to a given setting. A primitive describes a fundamental element of reasoning, in the sense that it is general to many different areas of experience. For example, to push a stationary box over a floor and to motivate an inherently lazy person both require an actuating agency. Or, when describing the motion of a box being pushed or the amount of work someone will do, more effort may be required to attain the same result, depending on the resistance to motion or work in the system. This primitive is referred to as the Ohm’s primitive, based on Ohm’s law, which describes the relationship between (output) current and (exerted) voltage, depending on the resistance of a circuit.

Many of the primitives that describe student reasoning come from investigations of student reasoning within Newtonian particle physics. These primitives include a set of primitives related to force and motion and a set related to collisions of objects. For example, students learning mechanics often use the actuating agency or Ohm’s primitives to describe the effects of forces on the motion of an object. Though appropriate when describing phenomena in a world containing friction, the use of these primitives often indicates that students are not reasoning in terms of physical laws such as Newton’s second law or are unable to interpret the many different elements of these laws in order to reach a complete and accurate description of the physics.

In addition to the primitives describing force and motion or collisions, students describing wave physics often make use of a previously undocumented primitive. I have documented student use of the *object as point* (or simply *point*) primitive in wave physics, but it is also commonly used in other areas. In the context of mechanics, it describes the useful manner in which objects are simplified to a single point when appropriate. For example, in free body diagrams or trajectory problems, an object is often described by a single point (the center of mass). Thus, the point primitive is useful and appropriate in many settings, but not necessarily in wave physics.

In the context of wave physics, students often use the point primitive inappropriately. In the context of superposition or the mathematical description of waves, many students seem to make use of it when they describe a wave by a single point, its peak amplitude. In the context of wave propagation, students might make use of it when describing how larger forces might lead to faster wave speeds. In this sense, the point primitive leads to the idea that a larger force can create a faster wave in the same fashion that a larger throwing force leads to a faster baseball.

Many students seem to inappropriately apply more than one primitive at the same time when describing wave physics. We can describe their reasoning in terms of a pattern of association, where these linked primitives seem connected in their reasoning. When asking students a series of wave physics questions on a specially designed diagnostic test, we see that they consistently make use of many of the primitives that are more appropriate in a mechanics than a wave physics setting. We describe student responses in terms of the *Particle Pulses Pattern of Association*, loosely referred to as the Particle Model, or PM. In contrast, we refer to the appropriate responses in a given situation as being indicative of the *Community Consensus Model* (or Correct Model, CM).

Curriculum Development to Develop Appropriate Student Reasoning

To help students move from a primarily PM based reasoning to a more appropriate CM based reasoning, we have developed a set of instructional materials called tutorials. The general design of tutorials as developed by the University of Washington, Seattle, is described in chapter 2. The tutorials designed at UMd as part of this dissertation and the description of their effectiveness in helping students develop more appropriate reasoning are given in chapter 6.

In tutorials, students work in groups of three or four on worksheets designed to change student reasoning about a specific topic. The three wave tutorials use the physics contexts of propagation and superposition, the mathematical description of waves, and sound waves to address many of the issues summarized above. In each tutorial, students view computerized videos of propagating waves to give the students the opportunity to see the otherwise very fast phenomena at a more interpretable speed. These videos were filmed by me and other PERG members and are commercially available as part of a video analysis software package, VideoPoint.

In the videos that students view while answering questions that deal directly with wave propagation issues, two wavepulses travel on two separate springs. Students must interpret the differences between the wave shapes and compare these differences to the possible differences in wave speed. When viewing the videos showing wave superposition, students are able to see that superposition occurs at all points in the medium where wavepulses coincide. They are then guided through activities that help them develop this idea more formally. In the wave-mathematics tutorial, students model the shape of a single wavepulse using both Lorentzian and Gaussian waveshapes. In the sound tutorial, students view a candle flame oscillating due to a sound wave. They graph the position of the candle as a function of time and use this information to develop ideas of period and frequency of sound. Further activities build on the video they have viewed and help students build an understanding of wavelength and the relationship between wavelength and frequency of sound.

To investigate the effectiveness of tutorials, we have compared student responses on a common set of questions before and after instruction. For each tutorial, we find that student performance improves more due to the tutorial than due to the traditional instruction that preceded it. For example, before instruction, only 9% of 137 students correctly state that a sound wave will make a dust particle oscillate longitudinally and another 23% state that the particle will oscillate but do not specify how. Some of the latter students describe transverse motion, possibly indicating that they are misrepresenting a displacement graph as a picture of the motion. The most common response is given by 50% of the students who state that the sound wave will push the dust particle away. Based on interviews we have done with students, we believe that this response is indicative of student use of the Particle Model, described above. These students seem to be applying inappropriate reasoning to their description of sound waves. After lecture instruction, 26% of these same students correctly describe the dust particle's motion (22% describe oscillation but not the direction), and 39% still describe the sound wave pushing the dust particle away. After tutorial instruction, 45% describe the motion correctly (18% more describe oscillatory motion without being clear about its direction), and only 11% describe the dust particle being pushed away by the sound wave.

Similar results are found in student responses toward wave propagation and superposition. Student performance both before and after lecture instruction indicate that many students use inappropriate reasoning when describing the physics of waves. The tutorials provide students with the opportunity to develop a more appropriate way of describing the physics, as can be seen from data indicating that far fewer students use the Particle Model after tutorial instruction than before. As a result, we believe that the tutorials are successful in helping students overcome the most common difficulties that they have with the material.

Investigating the Dynamics of Student Reasoning

As part of the investigation of the effectiveness of the tutorial materials, a diagnostic test was developed. This diagnostic test probed student understanding of wave physics in terms of student use of the PM and CM. In the final version of the diagnostic test, 137 students were asked eight identical questions dealing with propagation, superposition, and sound waves both before and after all instruction on waves. The diagnostic test contained both free response and multiple-choice, multiple-response questions. When a question was asked using both question formats, the free response question was asked first to prevent students from getting reasoning hints from the offered multiple-choice responses. Student responses were categorized according to whether or not their responses were indicative of either the PM or CM. Only students who answered a majority of the questions both before and after instruction were included in the analysis. Many students left some questions blank because they did not have time to complete either the pre- or post-instruction diagnostic, and many student responses were not classifiable as either PM or CM responses.

Before instruction, a majority of students use the PM in their reasoning. The average number of PM responses per student is 5.03 ± 2.02 (the standard deviation) while the average number of CM responses is 1.84 ± 1.71. Thus, we see that most students use the PM to guide their reasoning, and very few students use the CM consistently. After all instruction on waves (including tutorial instruction), students perform better. The average number of PM responses is now 1.68 ± 2.43, while the average number of CM responses is 3.73 ± 2.23. Students are using the PM much less often to guide their reasoning, but are also not using the CM as often as we would like.

In another analysis, we found that student use of multiple ways of describing the physics was not dependent on using appropriate reasoning in some topics of wave physics and inappropriate reasoning in others. Four of the questions on the diagnostic test addressed the physics of sound waves and the motion of the medium through which they travel. Student responses on these four questions before and after instruction are similar to their responses on the diagnostic test as a whole. Students begin the semester giving primarily PM descriptions of the physics, and end the semester using a hybrid of PM and CM reasoning to describe the physics. Thus, even in a specific area of wave physics, students give conflicting descriptions and show inconsistent reasoning.

Summary

In this dissertation, I have shown that it is possible to organize student reasoning in terms that give us deeper insight into their thinking about wave physics. I have defined the appropriate reasoning primitives, including a previously undocumented primitive called the *object as point* primitive. By organizing sets of commonly but inappropriately used primitives that students apply to the physics of mechanical and sound waves, we are able to discuss student difficulties with the material, the consistency of their reasoning, and how students develop their reasoning over time.

In much the same way that the use of certain primitives may be helpful in some settings but inappropriate in others, student use of the Particle Pulses pattern of association before students have received instruction on wave physics is understandable and not necessarily problematic. Students are applying the physics that they have previously learned and are trying to make sense of material with which they are usually not familiar. They are not always using correct physics in their reasoning, but we observe that students are trying to use their previous understanding to guide them in the new situation.

Student use of the inappropriate pattern of association after instruction is more problematic. Though we cannot compare tutorial students' performance on the diagnostic test to students who have not participated in tutorials, results from other investigations (such as student responses after lecture but before tutorial instruction) indicate that student are better able to reason effectively and accurately after they have participated in tutorial instruction. Further investigation would be required to determine what the differences are in student performance in a non-tutorial class, and to see what aspects of tutorial instruction are most effective in helping students develop more appropriate reasoning in our classes.

But even in a tutorial setting, students leave our classrooms using a mixture of appropriate, helpful ideas and inappropriate, problematic ideas. The research described in this dissertation shows that detailed descriptions of student difficulties with physics present a rich area of investigation relevant to both instructors and physics education researchers. For instructors, a more detailed understanding of possible student difficulties with the material can lead to more appropriate examinations and lecture materials that match more closely to students' actual needs. For researchers, the use of primitives, patterns of association, and mental models to describe student reasoning may provide a more appropriate language with which to describe the richness of student understanding of the physics.