Chapter 6: Development, Implementation, and Evaluation of Tutorials

Introduction

Once student difficulties have been found and described in detail, PER can serve as a guide for developing effective curriculum. These materials can aid students develop the difficult concepts that they will need to understand in their future studies in physics and other fields.

Many different types of research-based instructional curricula have been developed and evaluated for their effectiveness in teaching students relevant physics.[1] At the University of Maryland (UMd), the Physics Education Research Group (PERG) has introduced *tutorials*, a teaching method created and designed at the University of Washington, Seattle, by Lillian McDermott, Peter Shaffer, and the Physics Education Group.[2,3]

In this chapter, I will use the area of wave physics to illustrate how research-based curriculum development can create a productive learning environment for our students. The tutorials described in this chapter have been developed through an iterative process of research, curriculum development, implementation, and evaluation for a period of one to three years. Working in collaboration with other members of the Physics Education Research Group (PERG), I have developed a set of tutorials in wave physics which are designed to help students learn certain fundamental ideas in physics. The three tutorials discuss the physics of

- wave propagation and superposition
- the mathematical description of waves, and
- sound waves (propagation and mathematical description)

(Copies of the final versions of the tutorials can be found in Appendix A, B, and C. Unless otherwise noted, I describe the most recent version of each tutorial.) Throughout the tutorials, students discuss and develop the ideas of equilibrium, disturbances from equilibrium, propagation of a disturbance through a medium, effects of two disturbances meeting each other, and the mathematical description of a physical system through the choice of an appropriate model. These are skills which, to a certain extent, are illustrated best in wave physics but whose ideas are important in other areas of physics and in the students' subsequent studies.

In the sections describing each tutorial, I will discuss the research basis of each tutorial. In addition, I will discuss research results that suggest that tutorials are more effective than traditional instruction in teaching students the fundamental topics of wave physics. Many results come from a diagnostic test that is discussed in more detail in chapter 7.

One general point should be made when discussing the effectiveness of the tutorials with respect to student understanding of the material. Though the descriptions below imply that students receive an hour of instruction on the material being discussed, note that they are not receiving traditional recitation instruction. The time spent on the physics is roughly equivalent in the two settings, but the manner in which students interact and learn in the classroom is different. In the discussion below

I will emphasize what students do in the classroom and evaluate their performance based on the tutorial activities.

Creating Video Materials For Classroom Use

A central piece of each of the tutorials involves students viewing digitized videos of waves propagating on a long, taut spring. These videos were created in the Summer, 1995 workshop on Teaching Introductory Physics Using Interactive Methods and Computers, held at Dickinson College. As part of the workshop, John Lello and I carried out a project in which we created the videos and developed preliminary versions of some of the curriculum materials presented below. In this section, I will discuss how the videos were created.

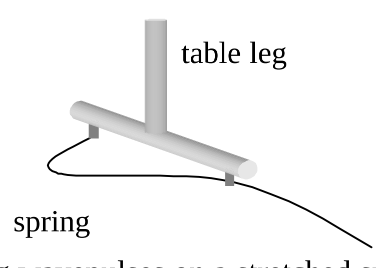
We stretched two long snake springs between two tables. A snake spring is a tightly coiled spring of roughly 1.5 cm diameter. The unstretched length of the springs was nearly 2 m. We stretched them to a tension of 10 N to 15 N and lengths of 4 m to 6 m, depending on the situation. On each end of the snake spring were loops (i.e., the last few coils of the spring, bent 90°). Each loop was fastened to the leg of a table by screws which are usually used to adjust the height of the tables. By keeping the table motionless (their weight held the springs firmly in place), we were able to keep the springs at a constant length and tension. Note that the spring was attached to the far leg of the table. The snake spring was free to move on only one side of the second table leg. See Figure 6-1 for a sketch of the set-up.

The waves used in the videos were created by pulling the spring through the gap between the table legs and releasing it. For example, by pulling the spring at exactly the midpoint of the gap between the two legs, we could create a triangular shaped pulse (see Figure 6-2).

The propagating waves were videotaped from a ceiling mounted camera whose signal was fed directly into a computer. The computer digitized the video signal immediately. This digitized video was then edited to include only the frames during which the wave was visible on the screen. Due to the design of the system, the speed of a propagating wave was approximately 8 m/s. Since the view field of the camera was roughly 2.5 m, the wave was visible on screen for roughly one quarter of a second. Since videotape is filmed at 30 frames per second, the wavepulses are visible in the videos for roughly 8 frames.

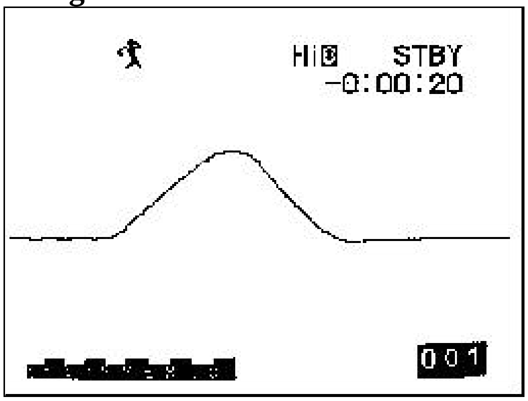
To videotape the wave propagating along the spring, a variety of problems had to be addressed. For example, the floor on which the spring rested was made up of

Figure 6-1



Sketch of set-up for creating wavepulses on a stretched snake spring. The spring is attached at one table leg and is pulled back by a hand (not shown). The spring is free to move along the second table leg.

Figure 6-2



Screen capture of "triangle.mov." The wavepulse moves from left to right along a stretched spring. The video is commercially available in the VideoPoint^{TM} software package.[5]

tiles, creating a low friction surface that prevented excessive energy loss to the system. Unfortunately, the tile floor also reflected the light from the room very strongly, making the silver snake spring difficult to see on the video. After much experimenting with different colors and materials, we found that a dark blue felt cloth created the best backdrop on which to see a moving silver colored spring. The higher friction from the new material did not seem to affect wave propagation or wave shape in any appreciable way. We were unable to compare the decrease in amplitude (equivalent to the loss in energy) between the two designs because we were unable to see the spring clearly when filmed on a plain tile floor. Using analysis techniques described below, we were able to show that the wavepulse on the felt floor lost roughly 10% of its amplitude over the course of the 8 frames on screen. This effect was considered unavoidable and small enough to be acceptable for our needs (mainly because the effect was very difficult to see on screen).

Another problem we had consisted of finding the right shutter speed for the video recorder. The wavepulses we created were roughly 50 cm in width at their base with an amplitude of roughly 50 cm. (Note that there are dispersive effects due to the large amplitude of the waves, but in the time scale we were observing, we could ignore these effects). With waves moving at 8 m/s, it would take a point on the spring 1/32 s to move from equilibrium to maximum displacement. With a frame rate of 30 frames per second, the slowest possible shutter speed was 1/60 s. (Video cameras use an interleaving technique such that the slowest shutter speed equals half the frame rate.) During this time, a piece of spring could move from equilibrium to maximum displacement. The slow shutter speed would create a blurred image on screen. As a result, we set the shutter speed of the videotape as high as the camera allowed (1/1000 s). We can estimate the speed of the piece of spring to be relatively constant for most of its motion away from the vertices of the triangular pulse shape, since we notice that the slope of the wavepulse is relatively constant in Figure 6-2. Thus, the piece of spring moves 1/2 m in 1/16 s, making an estimated speed of 8 m/s. During 0.001 s, the spring moves a distance 0.008 m, or just under 1 cm, which is slightly less than the diameter of the snake spring. This creates some smudging in the video, but only a negligible amount.

Two issues were problematic when making the superposition videos. In some of our videos, we show superposition of wavepulses moving toward each other from opposite ends of the spring. To create these videos, we had to make sure that the wavepulses met as close to the center of the videotaped area as possible. This meant that the people holding the spring on either of its ends had to release their hold within 1/30 s of each other. We came up with a rather elaborate counting scheme and rhythm to allow for this. In our first attempt at illustrating destructive interference, we managed to have the wavepulses meet within 10 cm of the center of the video screen. The one point on the spring that never moved was nearly perfectly located in the center of screen. (In destructive interference, there is an instant when the entire spring is at equilibrium, but only one piece of the spring is never in motion.) In the case of constructive interference, we were never able to have the point of maximum displacement closer than 1 m from the center of the screen.

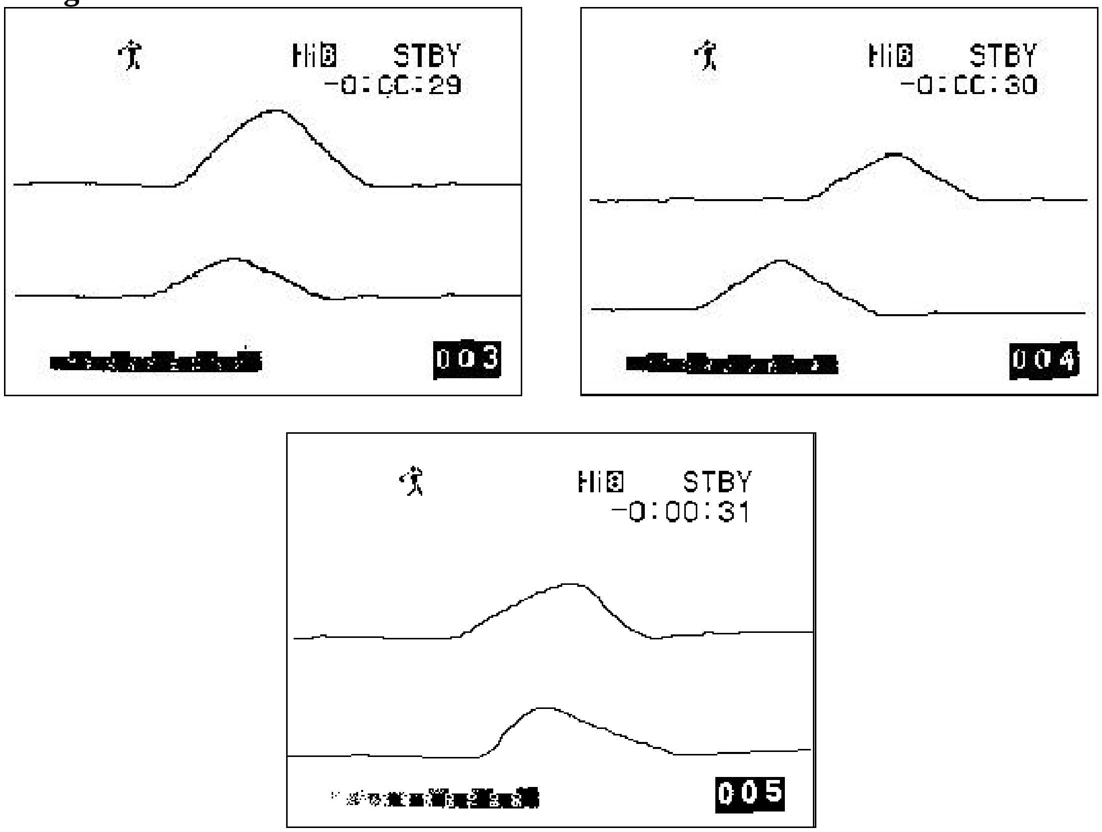
The second issue in creating the superposition videos involved the gross deformations to which we subjected the spring. When the two large amplitude wavepulses overlapped, the spring was stretched to an even larger amplitude. In the process, the dynamics of the system changed. Instead of the waves simply passing through each other at a constant speed, the time of the interaction was much longer than expected. Also, in the case of constructive superposition the moment of nearly perfect overlap of the peaks was captured on film. During this time, the amplitudes did not add up perfectly. We explain both of these phenomena by noting that the deformation to which the spring was subjected was much larger than the spring was designed for. In other words, the spring was simply unable to stretch enough. Later, when we attempted to stretch the spring to a similar length, we overstretched it and destroyed the tight coiling. This did not occur during the filming of the videos because the time scale of the stretching was so short.

In total, we created a set of ten videos of waves propagating on springs. The six that are used in tutorials are:

- *triangle.mov* – a single triangular-shaped pulse travels across the screen (see Figure 6-2),
- *diffside.mov* – two wavepulses on different sides of the spring meet and pass through each other,
- *sameside.mov* – two wavepulses on the same side of a spring meet and pass through each other,
- *diffshape.mov* – two asymmetric wavepulses with mirrored shapes travel side by side down two separate springs with identical mass density and tension (see Figure 6-3, video number 5),
- *diffamp.mov* – two wavepulses of different amplitudes travel side by side down two separate springs with identical mass density and tension (see Figure 6-3, video number 3), and
- *difftens.mov* – two wavepulses travel down two separate spring with different mass density and tension (see Figure 6-3, video number 4).

In the videos which showed a comparison of two different properties of the wave or the system, we had two springs lying side by side. We were able to create this situation by using both of the legs of the tables to which we had attached the springs. These table legs were separated by roughly one meter. We created different waves on each spring and were able to videotape how waves traveled side by side down the spring. Again, the timing issue played a role in creating these videos. We

Figure 6-3



Screen captures of the videos *diffamps.mov* (numbered 003 in the bottom right corner), *diffshape.mov* (005), and *difftens.mov* (004). The springs in *diffamps.mov* and *diffshape.mov* are identical and pulled to the same length and tension. The springs in *difftens.mov* are identical but stretched to unequal tensions (and therefore of different mass densities).

wanted the peaks of the waves to be side by side. This problem was easily solved by having one person with long arms hold each spring and release them at the same time. Examples of the video created can be seen in Figure 6-3.

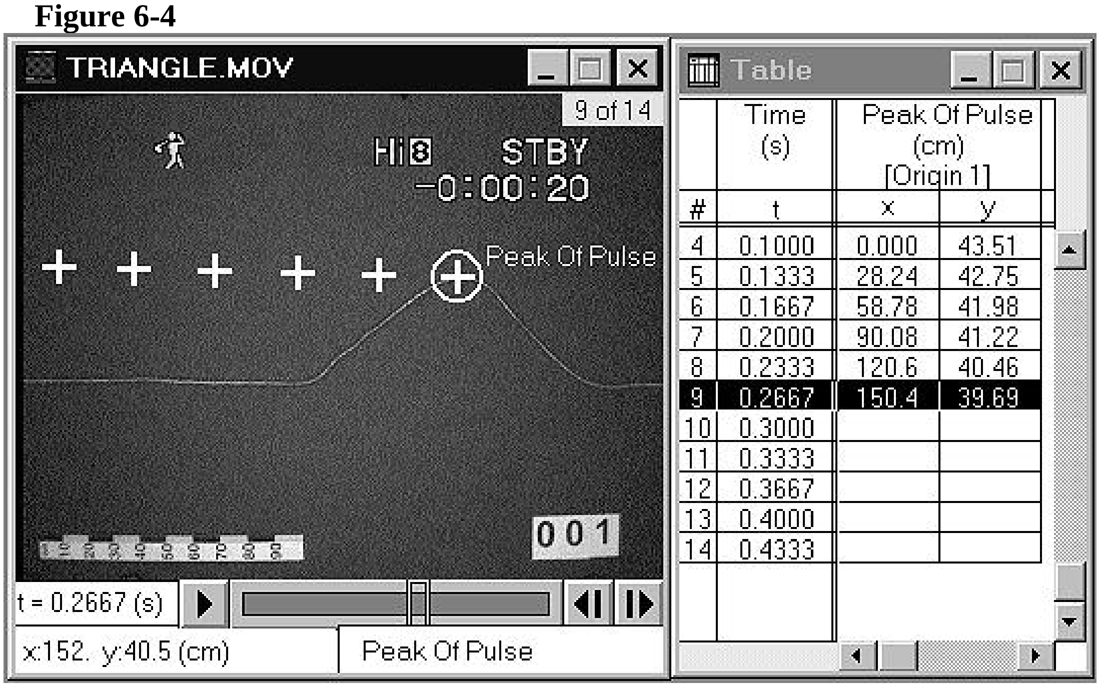
In the video *difftens.mov*, we had two springs of different tension. Note that the spring with the higher tension also had a lower mass density, since the higher tension was created by pulling the spring tighter. In this video, the timing issue was critical. We had calculated that in the given situation, the faster wavepulse would move roughly 1.4 times the speed of the slower wavepulse. The end of the video recorder's range was about 3 m from where the wavepulses were created. Therefore, the slower wavepulse moving at 8 m/s would reach this point in 3/8 s, the faster in 3/11 s (roughly 1/4 s). To have the faster wavepulse catch up to and pass the slower one while on screen, the faster wavepulse had to be released about 1/8 s later than the slower one. As with the video of destructive interference, the first attempt was the most successful. In this video, the faster wavepulse catches the slower wavepulse in the last frame of the video, such that their peaks are almost exactly lined up with each other.

To analyze the speed and the dimensions of the wavepulses on the video screen, we used two different software tools. The first was Apple Computer's *QuickTime*[4] multimedia software. Using this software, we could view the propagating waves and count how many frames it took the wavepulses to traverse a known distance (since we had determined the video's viewing range previously). This gave us a good estimate of the speed of the waves.

To gain more detailed measurements of the wave speed, amplitude, loss of amplitude, width, and other variables, we used software developed at Dickinson College. *VideoPoint*[5] software was in beta testing at the time of our summer workshop, but has been released since then. The videos described in this section form part of the commercially available software package and are available for use by anyone who purchases VideoPoint. To analyze the video, we begin by measuring a known length scale. In our case, we had placed a clearly marked and large meter stick in each of the videos. This meter stick is visible at the bottom left corner of each video screen capture shown in Figure 6-2 and Figure 6-3. By clicking on the each side of the meter stick, the person using the software can define a length scale for the images in the video. VideoPoint scales all distances on the screen according to the given length, and allows the person manipulating the software to use the cursor on screen to describe distances from an origin.

Measurements are made by placing the cursor at a location on the video window and reading its position off the screen (see Figure 6-4). Also, one can click on a given point, leaving behind a marker at that location. The position of this marker is then given in a data table. More than one marker can be placed, and the data table shows the coordinates of each marker at the correct time (where the time scale is

Figure 6-4



Screen capture from VideoPoint. The data point "Peak of Pulse" is shown for this frame, along with the time at which the frame is shown and the *x* and *y* position of the data point.

chosen in 1/30 s increments from the beginning of the video). As an example of how this allows measurements to be made, consider placing markers at the location of the peak of a propagating pulse. By measuring the location of the peak of the pulse in 1/30 s increments, we can show that the speed of the wave is constant as it crosses the screen. But, we can also show that the amplitude of the wave decreases by 10% from its original value. Students use VideoPoint mainly in the tutorial on sound waves, described below.

The video for the sound wave tutorial was filmed by Mel Sabella, also a member of PERG at UMd, during his stay at the 1996 Dickinson Workshop. In this video, a burning candle is placed roughly 5 cm from a large (25 cm diameter) loudspeaker. In this region, the waves from the speaker can be considered planar. By creating a low frequency but high volume wave, one can cause the candle flame to oscillate with an amplitude of roughly 4 mm. The physics of the situation have been discussed previously in chapter 3. In the video, we see the flame oscillating back and forth. The video was created by using a strong telephoto (zoom) to show both the loudspeaker and the flame. An image from the video is shown in appendix C in the tutorial on sound waves. The tutorial, discussed below, asks students to interpret the wave physics based on the oscillation of an element of the system through which the wave is propagating. To do so, they must make use of data gathered from VideoPoint.

The videos on mechanical waves and sound produced by the members of UMd PERG have been published and are commercially available on the VideoPoint CD,[5] where they can be found under the category "UMD movies."

Wave Propagation and Wave Superposition

Description of Tutorial

The Propagation/Superposition tutorial has been designed to address two profound difficulties that students show in pre-instruction investigations of their understanding. The tutorial is found in Appendix A of the dissertation. Through the use of video analysis, students have an opportunity to address their use of the Particle Pulses Pattern of Association (loosely referred to as the Particle Model, or PM, of waves). Our hope is that the tutorial will provide students with the opportunity to overcome their difficulties with wave propagation (i.e. the incorrect description that wave speed depends on the motion of the hand) and superposition (i.e. the incorrect description that waves add only at or with their highest points and nowhere else).

The tutorial we have developed is based partially on work originally done at the University of Washington, Seattle. Although much of our tutorial has been written to include video analysis of propagation and superposition, some parts still contain material from the UW tutorials. Interested readers can compare the UMd tutorial in Appendix A with the UW tutorial.[6]

Students begin with a pretest that investigates their understanding of wave propagation and wave superposition (see Appendix A). In taking the pretest, students are forced to think through the problem on their own, commit to an answer, and articulate that answer in writing. Because of the student difficulties we have found with the questions in the pretest, we believe the problems are both challenging and relevant.

In the tutorial itself, students begin by participating in a class-wide discussion based on demonstrations carried out by a facilitator. (This part of the tutorial is adapted from the one developed at UW.) In response to facilitator questions, students describe their observations of wave motion on a stretched snake spring (like the one used in the video). The facilitators use quick hand motions (a flick of the wrist back and forth) to give students an example of how to create a spring using a hand motion like the one presented in the tutorial. Students are asked to distinguish between transverse and longitudinal waves by comparing the motion of a piece of tape on the spring to the motion of the wavepulse. They are also asked to describe how different hand motions by the facilitator affect the shape of the wavepulse. Discussions led by the facilitator emphasize observations of how the shape and the motion of the wavepulse might be related. The facilitator also changes the tension of the spring and asks students to compare their observations with previous demonstrations of wave propagation. Class discussions use student terminology rather than imposing language from the facilitator. By constantly asking if the whole class agrees with a student's comments, the facilitator allows the students to regulate each other. Students build their understanding through observation and discussion. We find that the demonstrations alone are inadequate to help students observe certain aspects of wave propagation because students often see what they believe occurs rather than observing what actually happens.

Due to the high speeds of wavepulses in the demonstrations and student confusions about their observations during the class-wide discussion, the remaining activities in the tutorial attempt to address lingering difficulties. Students split into groups of three or four to work on the rest of the tutorial. They watch videos of wavepulses to view wave phenomena in slow motion. In these videos, individual wavepulses on two identical springs travel across the computer screen. Students use QuickTime[4] to advance the video frames individually or watch the whole video. In each video, wavepulses on the springs have some fundamental difference. Either their amplitude is noticeably different (*diffamps.mov*), their shapes are noticeably different (asymmetric triangular shaped pulses with mirrored asymmetry, *diffshape.mov*), or the tension in the springs is different. (Students are told this, since tension is not a directly observable difference, *difftens.mov*.) Figure 6-3 shows a typical screen shot of each of the videos.

For each video, students are asked to describe the hand motion that could have caused wavepulses with the shapes on the screen. For example, in *diffamps.mov*, the different amplitude wavepulses are of the same width at the base. Since the waves move at the same speed, equal width implies that the waves were created in the same amount of time. The distance of motion in the same amount of time differs, so the hand speed needed to create the different wavepulses hand differs. Those students who have stated on the pretest that different speed hand motions lead to different speed pulses must reconcile their expectations with observations of same-speed waves in the video. The movie *diffshape.mov* takes this idea further, showing that waves created through two different motions (mixed fast and then slow) would produce waves that travel at one speed. In the *difftens.mov* video, students are told that the tension in the springs is different. They observe different wave speeds, indicating that the tension on the spring affects the speed of wave propagation.

To further address student difficulties with the differences between transverse motion of the medium and longitudinal propagation of the wave, we next ask students to sketch velocity vectors for parts of a wavepulse propagating on a taut spring. Students use the wave motion to describe changes in position of the medium, and then use simple ideas of kinematics to describe the average velocity of the medium at different points. They describe that medium motion and wave motion differ in fundamental ways. These activities extend the previous discussion of differences between the motion of the medium and the motion of a disturbance to the medium by bringing in a more quantitative description of each motion.

After students have observed that the speed of the wave is constant at all times and that the motion of the medium is transverse to the direction of propagation, they predict the behavior of superposing waves. They are asked to sketch the shape of a string with two asymmetric wavepulses on it, much like on the pretest. The shapes given in the tutorial are chosen to match those on a video, “sameside.mov,” that students watch on their computers after making their predictions. Students are asked to account for the shape of the string at different times, and guided to an understanding that displacement of the string depends on the displacement due to each individual pulse. The rest of the tutorial develops this idea as students predict the effects of destructive interference and view “diffside.mov.”

Student Understanding of Wave Propagation

Student performance on both FR and MCMR wave propagation questions before and after tutorial instruction has been described in chapter 4. The tables showing student performance on the FR and MCMR question before and after instruction (as discussed in chapter 4) are shown in Table 6-1 and Table 6-2.

To use the language developed in chapter 5 to describe student performance after instruction, we found that students still answered many questions using the PM (speed depends on hand motion), though a greater number used the CM exclusively in their responses (speed depends on tension and mass density). Also, many students seemed to be triggered by the additional offered responses in the MCMR question into giving the CM response when they had previously given only a PM response. If we look at only the MCMR responses, we can still discern that many more students give an exclusively CM response and the number of students who give mixed CM/PM responses has gone down greatly.

The MCMR question is an interesting tool to evaluate lingering student difficulties with wave propagation after instruction because students already perform quite well on it before having any instruction on waves (in terms of recognizing the correct answer). The interesting measures in the MCMR question are how many students give completely incorrect (PM) responses or mixed (PM and CM) responses.

In addition to the tutorial classes described above, we have given the MCMR wave propagation question (after instruction) to 116 students who did not have a tutorial that specifically addressed their difficulties with wave propagation. In the S96 semester, students worked through a tutorial that did not include the use of videos in

Table 6-1:

(a)

	Speed changes due to change in:	Student responses on free response question: Only tension and density	both the medium and hand motion	the motion of the hand	other
Student responses On MCMR question	only tension and density	7%	1%	2%	1%
	both the medium and hand motion	1%	2%	60%	10%
	the motion of the hand	1%	1%	11%	3%

Comparison of student pre-instruction responses on FR and MCMR wave propagation questions, Fall-1997 (matched data, N=92). Students answered questions before all instruction.

Table 6-2:

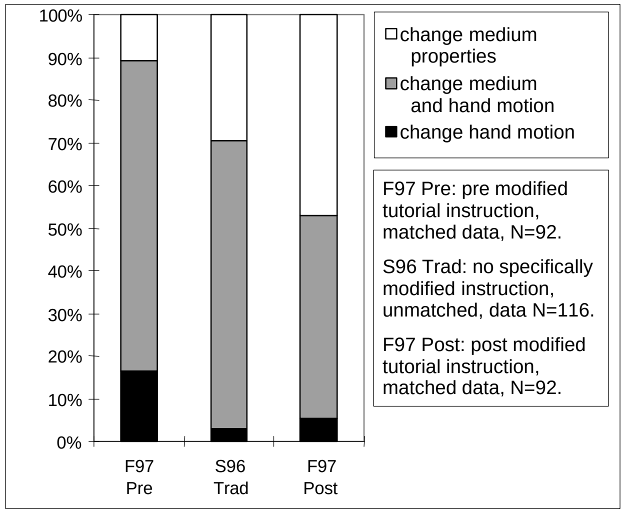
	Student Response:	Student responses on free response question: Only tension and density	both the medium and hand motion	the motion of the hand	Other
Student responses on MCMR question	Only tension and density	40%	2%	2%	2%
	Both the medium and hand motion	8%	17%	20%	2%
	the motion of the hand	2%	1%	2%	0%

Comparison of student post-instruction (lecture and tutorial) responses on FR and MCMR wave propagation questions, Fall-1997 (matched data, N=92). Students answered questions after all instruction on waves.

the same fashion as in F97. The class did not answer the FR question along with the MCMR question (as has been previously described in the dissertation) due to logistical reasons that prevented us from asking it that semester. We also do not have pre-instruction results from this class, but we suggest that the pre-instruction results from F97can be taken as suggestive of student performance in S96.

Figure 6-5 shows student performance on the MCMR question at three different stages of instruction. Note that some of the columns are matched (F97 data) while the middle column (from S96) is not. Also, we compared the performance of the F97 class as a whole to the performance of the matched students whose data is presented in the figure and found no great difference. The results show that students begin the semester (in F97) already using the correct response very often (more than 80%), but predominantly giving responses which we categorize with the PM (90%). After both traditional and tutorial instruction, nearly all students in both S96 and F97 semesters give the correct response (98%). But, in S96, after instruction that did not specifically address student use of the PM in wave propagation; nearly 70% give responses indicative of the PM. After instruction that addressed student use of the PM (in F97), roughly 50% of the students give answers consistent with the PM. These results illustrate the contrast of student answers among pre-instruction, post traditional instruction, and post modified instruction. (In this case, modified instruction that did

Figure 6-5



Comparison of student responses on the MCMR wave propagation question, F97 (matched pre/post tutorial instruction, N=92) and S96 (unmatched, post traditional instruction, N=116). Students answered the question on diagnostic tests given before and after all instruction on waves.

not specifically address the relevant issue is considered traditional instruction, since students did not receive any instruction on the material outside of the typical lecture setting). The effect of the modified tutorial instruction is evident when considering the differences in mixed CM/PM responses in S96 and F97. The results from F97 indicate that specially designed curriculum can play a role in affecting what is otherwise a very robust incorrect response.

Student Understanding of Wave Superposition

On the topic of wave superposition, we also see improvement in student performance after students participate in modified instruction. Student performance on wave superposition questions before any instruction, after traditional instruction, and after all instruction (including tutorial instruction) shows a definite shift in student performance and understanding of the physics of wave superposition. Table 6-3 shows student responses to the superposition questions asked during the course of the semester. The question shown in Figure 3-13 (described in chapter 3) was asked before and after all instruction. The question shown in Figure 3-9 was asked on a pretest which followed lecture instruction on superposition but preceded tutorial instruction. Only those students (N=131) who answered all three questions are included in the data.

At the beginning of the semester, only a quarter of the students correctly show superposition at all locations, while half the class gives answers which we have characterized as evidence of the PM. For example, they do not add displacement between the peaks of the wavepulses, they add the maximum displacement of each pulse even when the points of maximum displacement do not overlap, or they show

Table 6-3

Time during semester: MM used:	Before all instruction (%)	Post lecture (%)	Post lecture, post tutorial (%)
CM (point-by-point addition)	27	26	59
PM (only one point plays a role)	65	52	27
other	6	13	7
Blank	2.3	9.2	6.9

Student performance on wave superposition questions at different times during F97 (N=131 students, data are matched).

the waves canceling in the area where they overlap. We classify these responses as indicative of at least one aspect of the PM, as described in chapter 5.

After traditional instruction, students did not change their descriptions greatly. Even on a question that differed only slightly from the one asked at the beginning of the semester, one fourth answer the question correctly, and one half show evidence of the PM.

After tutorials, we see that the numbers have shifted dramatically. Nearly 60% of the students answer the question correctly, while slightly more than one fourth still show evidence of the PM. Based on these results, we claim that the tutorial has a strong effect on student understanding of wave superposition.

We must qualify this statement by showing evidence that problems persist. Before and after traditional instruction, 25% and 24% of the students (respectively) do not show addition of displacement between the wavepulse peaks (see Figure 3-13b). This accounts for 40% of the students who gave a PM-like response before any instruction and 50% of the students who gave a PM-like response after traditional instruction. (Other PM-like responses include showing waves as colliding, bouncing, canceling permanently, or adding amplitudes even when the peaks do not overlap.) After tutorial instruction, 17% of the students give the answer that there is no addition of displacement between the wavepulse peaks. This represents 63% of those showing evidence of the PM after instruction. A majority (68%) of the students who state before instruction that there is no addition between the peaks of the wavepulses do not change their responses after instruction. The students who move away from a PM-like response are those that gave other PM-like answers. This suggests that some aspects of PM reasoning when applied to superposition are very hard to overcome and that the present materials are not completely successful in suppressing student use of it.

Mathematical Description of Waves

Description of Tutorial

The tutorial that addresses the student difficulties with the wave-math problem described in chapters 3 and 5 is based directly on the wave-math problem itself (see Figure 3-7). In tutorial, groups of three or four students work through guided worksheets. The worksheet for this tutorial is included in Appendix B. Students begin by considering the mathematical form of a pulse at $t = 0$. In order to minimize the confusion related to the exponential, we begin this tutorial with the equation:

$$y(x) = \frac{50cm}{\left(\frac{x}{b}\right)^2 + 1} \tag{6-1}$$

where $b = 20\ cm$.[7] In order to help students develop a functional understanding of a function, they explicitly graph the shape of the string based on the equation representing its shape. Students are also given a screen capture of a propagating pulse (as shown in Figure 6-2) and asked to estimate the values of the amplitude and b in the equation above. (Though noticeably a very inexact Lorentzian pulseshape, the general shape is sufficient for this exercise and provides an excellent opportunity for discussion of modeling with the more advanced students.) When students are asked to sketch the shape of the spring on which the wavepulse is moving after the pulse has moved a distance of *3b*, we find that many sketch the shape with a lower amplitude. This is consistent with the analysis of the wave-math problem, where the variables x and y are misinterpreted as the location of the peak and peak amplitude of the pulse, respectively. Students are asked to watch a movie of the propagating pulse and those who made incorrect predictions based on the mathematics are confronted with their incorrect predictions and forced to describe the relationship between the mathematics and the physics. Thus, through their observations and their own reasoning, students see the need for modification to the mathematical function so that the wave shape stays the same while the shape propagates through the medium.

Students then sketch the shape the string would have after the pulse traveled some distance without dissipation, and are guided into constructing the mathematical form. In this way, students not only construct the shape of the string from an equation, they construct an equation from the shape of a string. After considering the functional form of the pulse at two different times, the students are given the opportunity to construct a single equation that describes the pulse as a function of both position and time. The key here is that it is the students that are constructing this equation based on their own work and on consideration of a specific physical system.

In the second part of the tutorial, students consider a pulse of a slightly different shape propagating on a string. In particular, they consider a pulse represented at $t = 0$ by the same equation considered in the pretest:

$$y(x) = Ae^{-\left(\frac{x}{b}\right)^2} \tag{6-2}$$

Students again are asked to construct an equation that describes the displacement of the string as a function of position and time. This time, students are not guided to this answer. Instead, they are forced to generalize their results from earlier in the tutorial and, when appropriate, resolve the conflict with their answers on the pretest.

In the final part of the tutorial, students apply and interpret the ideas that they developed by considering the motion of a tagged part of the string. Here they extract useful information about the motion of the tag by interpreting the mathematics of the problem. Because of student difficulties relating a physical situation to the corresponding equation, students use video software to mathematically model the shape of an actual pulse. As part of this, they explore the physical significance of the parameters *A* and *b* in equation 2 in more detail than they did with equation 6-1 in the first part of the tutorial.

The homework which accompanies this tutorial is given in Appendix B. Students apply the ideas covered in the tutorial while considering pulses of different shapes moving in different directions. They consider the shape of the pulses at different times physically and mathematically. They also consider the motion of the tagged part of the string in different situations.

Student Understanding of the Mathematics to Describe Waves

We have not investigated student understanding of the mathematical description of waves in as great a detail as other student difficulties for several reasons. To ask students to commit to answers about the mathematical description of waves (including two-variable functions) before instruction would be difficult with students who have no experience with such equations in physics. In addition, because of a shortage of time, we did not investigate this issue on the F97 diagnostic test. Finally, though certain examination questions were asked after student instruction on the mathematics of waves, no clear analysis of student understanding was possible because the questions asked avoided most of the issues which would have elicited student difficulties.

In S97, interviews were carried out with twenty students, fifteen of whom had tutorial instruction and five of whom hadn't. In these interviews, not all students answered the mathematics question because the question was not included in early versions of the diagnostic interview protocol. Of the 10 tutorial students who answered the question described in Figure 3-7 on the pretest before instruction, five sketched the shape of the spring with a smaller amplitude after it had propagated a certain distance, and none were able write a correct equation. Most who sketched a smaller wavepulse indicated that the exponential was the reason. Eight students plugged in x_0 or left x as the variable to describe the equation of the string. We consider that the PM can be used to describe both these responses. Students seem to be using the point primitive in their attempts to make sense of the mathematics, as has been discussed in chapter 5.

After tutorial instruction, student performance improved. Eight sketched the shape of the wavepulse correctly, and the two who did not indicated that they thought of the exponential term to guide their reasoning. Six of the students wrote the correct equation, though four of the students either plugged in x_0 or x to describe the shape of the string. The tutorial seems to have addressed some of the students' difficulties. More research needs to be done to investigate student understanding more deeply.

Sound Waves

Description of Tutorial

The sound tutorial, like the previous two, builds on our observations of student difficulties with fundamental ideas of physics. These difficulties have been illustrated in detail by quotes from interviews with Alex presented in chapter 3 and Kyle presented in chapter 5. In the discussion of student difficulties with sound waves, student difficulties have been described in terms of the description of the motion of a dust particle. The tutorial discusses the motion of the medium through which sound waves move in the context of an oscillating candle flame. Data from a pretest from F97 (see Table 6-4) show that students have generally the same difficulties with describing the motion of a candle flame that they have with describing the motion of a dust particle. Only matched data are presented in the table. Note that the high number of blank responses on the candle flame response are due to the candle flame question coming in the later half of the pretest. Since the pretest was asked in one class (of the two that took it) on the same day as a mid-term examination, many students simply did not attempt the majority of the pretest. Also, their time was much shorter than the students in the other class. Still, the data are very similar, suggesting that the context of the tutorial is relevant to student understanding of sound waves. Detailed results will be shown below.

In the tutorial, students begin by predicting and then viewing a video of the motion of a single candle due to a sound wave coming from a large loudspeaker. Students must describe the motion of the candle due to the sound wave, and must resolve any conflicts between their predictions and observations. In addition, we ask that they explicitly apply their predictions to the context of the dust particle that was part of the pretest.

In the next section of the tutorial, students are given data that shows the position of the left edge of the candle flame at different times. The data points have been taken beforehand using the program VideoPoint[5] (see above for a description of

Table 6-4

Object Whose Motion is Being Described MM used:	Dust Particle (%)	Candle Flame (%)
CM (longitudinal oscillation)	22	39
Other oscillation	26	3
PM (pushed away linearly or sinusoidally)	38	21
Other	11	17
Blank	3	20

Performance on student pretest, comparing descriptions of dust particle and candle flame motion. Students answered the two questions at the same time (F97, data are matched, N=215). The high number of blank responses on the candle flame question is due to lack of time during the pretest, which was followed by an mid-term examination.

VideoPoint) and are presented to the students in a data table in the tutorial. Due to time limitations during the tutorial, students are not asked to take the data themselves. In the tutorial, students must observe the connection between the data points and the cross-mark on the screen. Students are asked to graph the data points on a provided graph. From the graph, they then find the period of the sound wave. In the activity, students go from a description of a single candle (which represents the motion of the medium) to describing the frequency of the sound wave. Thus, they are given the opportunity to connect observations, mathematical descriptions, and physical properties that they have discussed in class and used in their homework.

Students are then presented with a photograph of *two* candles sitting in front of a loudspeaker. They are asked to describe the motion of both candles and to sketch separate displacement vs. time graphs for each candle. To answer the question, students must generalize from their previous description of a single candle's motion to think about any possible changes between the motion of the first and the second candle. Students must use the idea of a propagating wave with a finite speed to develop the idea of a phase difference between the motion of the two candles. This idea is developed through a Gedankenexperiment where students are asked to think of more and more candles placed at different locations along a path away from the speaker. They are asked to sketch the displacement from equilibrium of each candle at a specific instant in time. From this activity, they able to find the wavelength of the sound wave. Again, students are given the opportunity to connect their mathematical knowledge from class with reasoning based on simple ideas that build on the model of wave propagation from the previous two tutorials.

The ideas of wave propagation and wave-math form an integral part of students' opportunities to build an understanding of the phase difference between parts of the medium which are different distances from the wave source. Thus, at the end of the tutorial, students have had to revisit material and concepts from their first two tutorials. They have built a model of waves as propagating disturbances, and they have described the propagation of these disturbances on a taut spring. In the sound wave tutorial, students use this model of wave propagation to describe a different area of physics. They are able to develop the idea that the concepts discussed in the tutorials are general and applicable to different topics that are more general than the specific areas in which they were first developed.

Student Understanding of Sound Waves

The sound waves tutorial was developed after preliminary results showed that students' difficulties were not changing as a result of traditional lecture instruction. At the end of F95 (after all instruction) and the beginning of S96 (after all instruction), students answered identical questions. They were asked to describe the motion of a dust particle after a loudspeaker has been turned on. Student difficulties with this topic have been discussed in detail in chapter 4.[8] Table 6-5 shows student performance in these two semesters. The data are not matched, since different student populations were involved in the testing. We see that lecture instruction makes no sizable difference in student performance. The comparison between student responses from F95 and F97 is illustrative of the effect of the research-based tutorial instruction.

Table 6-5

Time during semester: / MM used:	Before all instruction S96 (%)	Post lecture F95 (%)
CM (longitudinal oscillation)	14	24
Other oscillation	17	22
PM (pushed away linearly or sinusoidally)	45	40
Other and blank	24	14

Comparison of student responses describing the motion of a dust particle due to a loudspeaker. Data are from F95 post-instruction and S96 pre-instruction and are not matched (S96, N = 104; F95, N = 96)

In the beginning of F97, students answered a question (shown in Figure 3-3a) in which they had to describe the motion of a dust particle due to a sound wave. This same question was asked in a pretest in which a question about the motion of a candle flame due to a sound wave was also presented. (Note that Table 6-4 compares student performance on the dust particle question and the candle flame question which is similar to the actual content of the tutorial.) Finally, the dust particle question was asked against the end of the semester. The data comparing student responses to the dust particle question at these three times are shown in Table 6-6.

We see that students show little difference in their performance before and after traditional instruction on sound. They have profound difficulties connecting the physics that is taught in the classroom to any simple physical situations that might help them imagine and understand the situation in detail. After the tutorial, a much larger number of them are able to describe the correct motion of the dust particle. The large increase in the CM response and the large decrease in the PM response indicate that the tutorial is having a strong effect on student understanding.

Though the improvement in student performance is encouraging, we still see lingering difficulties. The total number of students giving CM responses is still less than 2/3 of the class. Also, a large number are still unsure of longitudinal or transverse oscillation of the dust particle, showing that the mathematical and graphical representations we use in class may adversely affect student reasoning about the physics.

Table 6-6

Time during semester: / MM used:	Before all instruction (%)	Post lecture (%)	Post lecture, post tutorial (%)
CM (longitudinal oscillation)	9	26	45
Other oscillation	23	22	18
PM (pushed away linearly or sinusoidally)	50	39	11
Other	7	12	6
Blank	11	2	21

Student performance on sound wave questions before, after traditional lecture, and after additional modified tutorial instruction. Data are matched (N=137 students). The large number of blank responses in the post-all instruction category is due to the number of students who did not complete the pretest on which the question was asked.

Conclusion

Tutorials have been designed to replace the smallest possible amount of the common lecture format by replacing the one hour, traditional, TA-led recitation with a set of group activities that provide students with the opportunity to develop their own understanding of the physics while interacting closely with their peers and facilitators. In this chapter, I have shown that research into student difficulties can lead to more effective instruction.

The tutorials described in this chapter serve as an example of the curriculum development that can grow out of research into student difficulties. By knowing student difficulties with wave propagation, we were able to design video-based activities that helped students visualize the manner in which waves propagate. We were also able to provide students with a set of videos that allowed them to see the process of superposition. The relationship between the mathematics and physics of propagation (i.e. the relationship between functions of two variables and the physical situation) was investigated through simple activities that helped students develop the idea of a coordinate transformation without explicitly stating that this is what they were doing. In the sound wave tutorial, the ideas of the previous two tutorials were used to help students move from a description of a piece of the medium to the description of the sound wave making the medium oscillate. Each of these activities is related to an area in which we have found that students have difficulty.

The tutorials have met with measurable success. In some cases, such as sound waves and superposition, students show great improvement in their ability to describe the correct physics. In other cases, such as propagation, we find that the room for improvement is not as large, since many students enter our classes already aware of the correct answer. But after tutorial instruction, a larger fraction of students give <u>only</u> the correct answer when answering FR and MCMR questions, showing that the strength of their understanding has changed. Finally, in the case of wave-math, we have not been able to carry out sufficient investigations to show whether or not the tutorial shows great improvement over traditional instruction. Preliminary results are encouraging, but more work needs to be done.

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[1] For a discussion of different research-based curricula and their effectiveness at the introductory level, see chapter 1, reference 1 (the UMd dissertation in physics by Jeff Saul).

[2] A discussion of the tutorials and the role of research in their development can be found in McDermott, L. C., "Bridging the gap between teaching and learning: The role of research," AIP Conf. Proc. **399**, 139-165 (1997). In addition, a sample class on the tutorials was presented at this conference. See McDermott, L.C., Vokos, S., and Shaffer, P. S., "Sample Class on Tutorials in Introductory Physics," in the same Proceedings. For other examples of tutorials and of the research that underlies their development, see the discussion in chapter 2.

[3] For a description of the development and investigation into the effectiveness of tutorials at UMd, see Redish E. F., J. M. Saul, and R. N. Steinberg, "On the effectiveness of active-engagement microcomputer-based laboratories," Am. J. Phys.

65 45-54 (1997) and Steinberg, R. N., M. C. Wittmann, and E. F. Redish, "Mathematical Tutorials in Introductory Physics," AIP Conf. Proc. **399** 1075 - 1092 (American Institute of Physics, Woodbury, NY 1997).

[4] QuickTime is a cross-platform multi-media software package and is a registered trademark of Apple Computer (www.apple.com). More information can be found at URL www.apple.com/quicktime.

[5] The VideoPoint™ CD-ROM is a video analysis program developed at Dickinson College by P. Laws and Mark Luetzelschwab. It is commercially available from Lenox Softworks, Lenox MA.

[6] McDermott, L. C., P. S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics* (Prentice Hall, New York NY, 1998).

[7] We have found through informal observations and one interview that many students interpret the variable x in this equation similarly to how they interpret it in the exponential equation discussed in chapter 4. These students fail to include a time variable in the equation and interpret x to mean the location of the peak of the pulse.

[8] Because the diagram included with the question indicated walls which created a tube around the dust particle, we saw a variety of additional answers which went beyond those discussed in chapter 4. In many, students seemed to use the walls to guide their reasoning; the existence of the wall seemed to trigger responses dealing with harmonics in closed tubes. A non-trivial set of responses involved the sketching of standing wave patterns in the tube. In later semesters, we removed the walls from the question to provide more clear insight into student difficulties with the fundamentals of the physics of sound.