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Investigating Student Understanding of Sound as a Longitudinal Wave

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INVESTIGATING STUDENT UNDERSTANDING OF SOUND AS A LONGITUDINAL WAVE

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The field of physics education research (PER) has highlighted the discrepancy between what is taught during traditional instruction in physics, and what students understand afterward. PER has also provided alternatives to traditional instruction that are research-based and have been shown to be more effective in bringing students' level of understanding of physics more in line with that of the scientific community. One topic that has received attention is the propagation of sound.

We confirmed that students in the introductory algebra-based and calculus-based physics courses at the University of Maine have difficulties with sound propagation similar to those documented by others. We found that a relatively small percentage of the students we interviewed from a calculus-based introductory physics course used the community consensus model of particles oscillating parallel to the direction of propagation. We identified three other mental models used by the interview subjects that have been described previously. The first was a model in which sound is considered to be an entity that passes through the medium without disturbing the particles of the medium. The second was a model in which sound is viewed as an entity that pushes the

particles of the medium aside as it propagates. The third was a hybrid model in which the particles of the medium oscillate perpendicular to the direction of propagation.

In an extension of the work by previous researchers in this area, we examined students' ability to predict the points at which the particles of the medium have the maximum and the minimum magnitudes of velocity and displacement from their equilibrium positions. We found that students' ability to do so was extremely limited.

To improve student understanding of sound propagation, we developed an instructional tool in the form of a "tutorial" and evaluated its effectiveness through pre- and post-testing of students enrolled in an algebra-based introductory physics course. The tutorial constructed for this purpose was found to be successful in increasing the number of students that used the community consensus model when answering questions about sound propagation. It was less successful in enabling students to make accurate predictions about particle velocities and displacements.

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CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1. Introduction

In recent years there has been significant interest in the field of Physics Education Research. This research has highlighted the ideas that students bring to an introductory physics course, the degree to which these ideas interfere with achieving instructional goals, and the failure of traditional instruction to bring about changes in these ideas.

One topic that has attracted a moderate level of interest is the propagation of sound. While this topic is familiar to most students, including many in the elementary grades, previous research has shown that many students do not have a clear understanding of what happens to the particles of the medium when a sound wave is propagated. This study replicates certain aspects of prior research on the propagation of sound, and expands upon it. Through interviews, the ideas that students in an introductory calculus-based physics course at the University of Maine had about propagation of sound were investigated. Following this first phase of the study, alternative instructional materials were developed, used with an introductory algebra-based physics course at the University of Maine, and their effectiveness evaluated through pre and post-testing.

1.2. Problem Definition

This study was designed to determine if students in the introductory algebra-based physics course at the University of Maine utilize models for sound propagation that have been identified in previous research at other locations, and to change students' understanding of longitudinal wave propagation so that it more closely aligns with the scientifically accepted view.

1.3. Rationale for Selecting Sound Wave Propagation as a Topic

Sound is the category of longitudinal wave phenomena that is most familiar to the largest number of people. For this reason, sound was selected as the topic for this investigation into student understanding of longitudinal waves.

Although wave motion is typically considered an essential component of a comprehensive introductory course in physics, emphasis is customarily placed on the properties and behavior of transverse waves. Less attention is paid to longitudinal waves in general and to sound in particular. This stems in part from the assumption that students in middle school and high school have studied sound in some detail. Sound is also considered a topic that does not contain complex ideas (Linder 1993). In actuality, as documented in Chapter II, there is much evidence indicating that sound is not a well understood topic, even after students have been exposed to traditional instruction.

Of the possible aspects of longitudinal waves that could be examined, propagation was chosen because it is fundamental to an understanding of many other properties. An understanding of standing wave phenomena, for example, requires comprehension of wave propagation as well as an understanding of reflection and resonance.

While several studies have examined student understanding of sound propagation, they have not explored student ideas about the behavior of the particles of the medium in detail as this study does.

1.4. Research Questions

The three primary research questions that this study was designed to answer are:

- What models of sound wave propagation do students in introductory physics courses at the University of Maine employ prior to implementation of a research based curriculum reform effort, and are these models similar to the models used by students in other populations?
- Is it possible to develop instructional materials that significantly increase the number of students utilizing the community consensus model for the propagation of longitudinal waves in general, and sound in particular?
- To what extent can students assimilate a mental model that will enable them to accurately describe, in detail, the motion of the individual particles of the medium as a longitudinal wave is propagated through it? Accurately describing in detail is defined as being able to identify the particles in the medium that have a maximum and a minimum magnitude for their acceleration, velocity, and displacement from the equilibrium position as a longitudinal wave is being propagated through the medium.

1.5. Overview of the Study

1.5.1. Evaluating the Initial State of the Sample Population

To answer the research questions it was first necessary to determine if the ideas exhibited by students in the sample population related to propagation of longitudinal waves, matched student ideas identified in previous research. This was accomplished through an interview process. In all, nine students from an introductory calculus-based physics class (PHY 122) were interviewed. The initial interview protocol contained only questions related to longitudinal waves. The protocol was modified after two students were interviewed; questions about transverse waves were added for comparison purposes. The protocol was adjusted one additional time before the last three students were interviewed. Results from these interviews were used to develop a pretest and a post-test for the actual target population, students in the algebra-based introductory physics course at the University of Maine (PHY 112). This information was also used to develop the instructional materials that were tested with the target population.

1.5.2. Altering Student Understanding

Although traditional instruction has been found to be ineffective in changing the deep-seated ideas that students bring to the classroom, physics education research has identified some promising alternatives. Among these is the use of the "tutorial" as an instructional tool. Tutorials are small-group, guided-inquiry, conceptually oriented exercises. Tutorials were first developed and then used extensively by McDermott and Shaffer (2002). They have since been used in a wide variety of settings by many instructors. During the course of completing a tutorial, students explore situations that challenge common misconceptions, and construct models that more closely match scientifically accepted ideas. A tutorial was developed for this project that reinforced the scientifically accepted model for propagation of sound, and challenged the other common models identified through the interview process and a review of previous research. The tutorial also asked students to explore the behavior of the particles of the medium during longitudinal wave propagation. Students encountered the idea that the behavior of the particles of the medium could be understood if their behavior was modeled as simple harmonic motion. They were then asked to use their knowledge of simple harmonic motion to predict which particles were experiencing the maximum and the minimum magnitudes of force, acceleration, velocity and displacement from the equilibrium position.

1.5.3. Assessing the Impact of the Project

A pre test and a post-test were developed. These instruments assessed student understanding of sound propagation and the behavior of the particles of the medium during longitudinal wave propagation. Results from the pre- and post-tests were used to evaluate the effectiveness of the tutorial.

1.6. Synopsis of the Thesis

Chapter I of this thesis presents an overview of the content of the thesis. Chapter II is a review of the literature pertinent to the thesis. Three areas are examined, research on ways of describing student thinking about physics, research on student ideas about longitudinal waves and sound, and research on curriculum reform efforts. Chapter III presents information gained from interviews with students. Chapter IV describes the reform effort that was carried out. Chapter V details the effects of using the tutorial as determined through pre and post-testing. Chapter VI summarizes the conclusions reached from this study and suggests some areas where further work is possible.

CHAPTER 2

REVIEW OF THE PERTINENT LITERATURE

2.1. What It Means to Understand

Understanding implies the ability to employ a set of ideas and relationships in a variety of contexts to generate reproducible outcomes. Ideally these outcomes should be identical to the outcomes obtained by experts in the field. Unfortunately, there is much evidence to suggest that a significant number of students in introductory physics courses lack the desired level of understanding of many physics concepts.

The naive view that a student entering a classroom for the first time is a “tabula rasa,” a blank slate, ready to be inscribed by the instructor, is comforting, but falls far short of the mark. The results from much educational research, an extensive listing of which has been compiled by McDermott (1999), clearly indicate that students’ initial states are far more complicated. Each has a mental framework that has been constructed based on the experiences that individual has had. Very often, careful questioning reveals that a student’s mental framework leads to answers that are markedly different from those of an expert in the field. A number of attempts have been made to describe these mental frameworks, each with its own vocabulary.

2.1.1 Student Conceptions

When students’ mental frameworks do not produce results in line with the community consensus, they have been referred to as “common sense theory” (Halloun & Hestenes 1985), “intuitive physics” (Viennot 1985), “conceptual schemes” (Driver 1989), mental models (Redish 1994), “misconceptions” (Hammer 1996), and “alternative conceptions” (Palmer 1997). These terms attempt to give a name to something that is quite complicated. Driver states, "… decades later there is an extensive literature that indicates that children come to their science classes with prior conceptions that may differ substantially from the ideas to be taught, that these conceptions influence further learning and that they may be resistant to change." A common theme among these descriptors is the core idea of conceptions. Hammer (1996) identified four characteristics that are encompassed by the idea of conceptions. According to Hammer, conceptions:

1. "are strongly held, stable cognitive structures";
2. "differ from expert conceptions";
3. "affect in a fundamental sense how students understand natural phenomena";
4. "must be overcome, avoided, or eliminated for students to achieve expert understanding."

These mental frameworks can prove exceptionally difficult to change for several reasons. According to Viennot (1985) intuitive physics is at least partially self-consistent. Students usually are not aware of the inconsistencies that arise between the mental frameworks they develop and generally accepted physics principles and therefore do not spontaneously confront the conflicts that arise. Palmer (1997) argued that, in at least some cases, students' mental frameworks were "theory like" and consisted of a coherent internal structure that is used in different contexts. Hammer (1995), on the other hand found evidence that students used a mixture of concepts and were not consistent in applying them from one situation to another.

Further evidence of the complexity embodied in these terms is provided by Maloney & Siegler (1993). They identify three frameworks that characterize the learning process. The first framework involves, "… a change from absence to presence of relevant physics concepts." The second framework involves, "… a change from intuitive understandings of physical phenomena to understandings consistent with physics principles." The third framework, the one they propose, purports that "… the student might both enter and leave the course with several different understandings of relevant concepts…" They believe that the formal understandings learned through instruction coexist and compete with, rather than replace, the informal understandings that they bring with them upon entering the course.

The "common sense theory" of Halloun and Hestenes (1985) has elements in common with the "conceptions" idea. They identified two general conclusions from research regarding common sense theory:

1. "Common sense beliefs about mechanics are generally incompatible with Newtonian theory."
2. "Common sense beliefs are very stable and conventional physics instruction does little to change them."

Viennot sees "intuitive physics" as representing a self-consistent collection of concepts and relationships with similarities to historical stages in the development of physical theories. She also characterizes them as particularly resistant to change.

In describing "mental models," Redish (1994) ascribes to them the following properties:

1. "They consist of propositions, images, rules of procedure, and statements as to when and how they are to be used."
2. "They may contain contradictory elements."
3. "They may be incomplete."

4. “People may not know how to ‘run’ the procedures present in their mental models.”
5. “Elements of a mental model do not have firm boundaries. Similar elements may get confused.”
6. “Mental models tend to minimize expenditure of mental energy.”

2.1.2. P-prims and Resources: Alternative Formulations

One difficulty with the conceptions description of understanding is the implicit idea that students’ initial ideas are incorrect and must be replaced with accepted physical theories. This is the objective of traditional instruction. Unfortunately, traditional (lecture-based) instruction has been found to be ineffective in changing students’ most deep-seated conceptions. Constructivism, an alternative model for learning, is at odds with misconception research (Smith 1993). Constructivism involves a gradual change from existing knowledge to accepted physical theory. Constructivist learning is fostered by an understanding of student thought processes that are, at least in some contexts, correct. Many of the modern curriculum reforms that have been shown to be more effective than traditional methods are based on constructivism.

An alternate description of student understanding has been proposed by diSessa (1993, 1998). In his model, diSessa considers only one category of concepts and calls these concepts “coordination classes” (diSessa 1998). Coordination classes are systematically connected ways of getting information about the world.

A coordination class has two major components. The first of these is a collection of “readout strategies.” Readout strategies extract from the information available, characteristic attributes that a concept exhibits in different situations. Readout strategies are primarily used to determine the value of a quantity.

The second major component of diSessa's model is what he calls the "causal net." According to diSessa (1998), "The general class of knowledge and reasoning strategies that determines when and how some observations are related to the information at issue (that is, related to 'determining the value of the quantity') is called a causal net."

At the foundation of diSessa's descriptions of the "causal net" are "phenomenological primitives", or p-prims. "P-prims are rather small knowledge structures, typically involving configurations of only a few parts that act largely by being recognized in a physical system or in the system's behavior or hypothesized behavior." (diSessa 1993). They usually represent abstractions of common experiences and are used as if they required no justification. P-prims are inherently neither correct nor incorrect. The context within which a p-prim is used determines if employing the p-prim will produce a result in alignment with accepted physical theory. An example of a p-prim is "closer means stronger," the idea that an effect is stronger the closer you are to the source. A student applying this p-prim to making predictions about the light coming from a light bulb or the sound coming from a speaker will arrive at a correct conclusion. Applying this p-prim when trying to explain why it is warmer during the summer than during the winter will lead to the incorrect conclusion that it is because the earth is closer to the sun in summer.

An organizational structure similar to deSissa's was described by Hammer (2000). He proposed the term "resources" to describe the tools that students employ when analyzing physical situations. He uses the analogy of a chunk of computer code that can be incorporated into many different programs. In the same way, resources are ways of thinking, developed as a consequence of life experiences and schooling that can be used in a wide variety of situations. Like p-prims, they may be used in ways that lead either to correct or incorrect conclusions.

Hammer (2000) identified two distinct needs for the development of scientific understanding related to resources:

1. "the formulation of intellectual resources"
2. "the (re)organization and application of these resources to align with scientific knowledge and practices."

He felt that the first need was best met by science education in the early grades, and that the second need should be addressed at the high school and college level.

For the purpose of this study, the term "mental model" will be used in describing student ideas about waves and sound. Mental model captures, to some extent, the subtleties described by diSessa's coordination classes. It also avoids the implication that these ideas are incorrect and must be replaced by accepted physical theory.

2.2. Student Ideas about Waves and Sound

Sound is a topic which does not typically receive a thorough treatment in introductory physics courses. According to Linder (1993) this is because it is assumed that it is either a topic which does not contain complex ideas, or that it has been studied in some detail in secondary school. As a consequence, the level of interest related to student understanding of sound has been much less than the interest generated by other areas of physics (Wittmann, Steinberg, and Redish 2003). An examination of the research that has been done pertaining to student understanding of sound reveals that this topic is much more complex than it appears at first glance, and that students have deeply rooted ideas that do not conform to accepted scientific explanations for sound phenomena.

In "Teaching Introductory Physics," Arons (1997) describes a number of difficulties related to student understanding of waves. Students sometimes fail to recognize that the propagation velocity of waves is different from the velocities of the individual particles of the medium. This is due in part to a failure to perceive that the velocity of a particle of the medium varies in time, and varies from one particle in the medium to another. Arons (1997) also suggests that longitudinal waves are not well understood. Students fail to grasp the fact that while a single positive transverse pulse can be generated by displacing the end of the spring and returning it to its equilibrium position, to generate a single compression pulse, the spring must be displaced and left displaced in the direction of the compression. Furthermore, he states that students most frequently visualize sound waves in terms of the microscopic distribution of the particles of the medium (usually ignoring the thermal motion of the particles), rather than from a macroscopic point of view involving pressure and density.

Much of the work that has been done on student understanding of sound involves propagation of sound. The reasoning that is most prevalent when students are asked to explain phenomena associated with the propagation of sound focuses on sound as an entity. Linder and Erickson (1989) identified the following ideas that seem to guide student reasoning about sound:

1. “Sound is an entity that is carried by individual molecules as they move through a medium.”
2. “Sound is an entity that is transferred from one molecule to another through the medium.”
3. “Sound is a traveling bounded substance with impetus, usually represented in the form of flowing air.”
4. “Sound is a bounded substance in the form of some traveling pattern.”
5. “Sound is linked to the concept of waves as part of a mathematical physics modeling system (and in this context could not be distinguished from light: the wave equations looked identical).”

They also found that confusion is caused when sound, a longitudinal wave, is depicted using transverse representations in textbooks. As a consequence of these representations, Linder and Erickson found that students often perceived the envelope of the wave as being synonymous with a transverse wave. They also found that these representations caused students to think that particle displacement, changing sound pressure and changing molecular velocities are all in phase with each other. As a consequence, they see equilibrium positions as stationary positions.

Linder (1993), found that students had three qualitatively different ways of conceptualizing sound propagation as it related to factors affecting the speed of propagation.

1. “The speed of sound is a function of the physical obstruction that molecules present to sound as it navigates its way through a medium.”
2. “The speed of sound is a function of molecular separation.”

3. The speed of sound is a function of the compressibility of a medium (the more compressible the medium the faster the propagation and vice versa)."

In the first conceptualization, students viewed sound as a "thing" that was slowed down by obstacles as it travels through a medium. The larger the particles or the more numerous the particles, the slower the sound will travel.

In the second conceptualization, students also view sound as an entity. In this case the speed is determined by how far a particle must travel before transferring the sound to another particle. Consequently, using this conceptualization, students would conclude that sound would travel more quickly in more dense media.

In the third conceptualization, the characteristic that determines the speed is the compressibility of the medium; the more compressible the medium, the faster the sound would travel. As in the other two conceptualizations, sound is perceived as a "thing" that is transferred through the medium, particle to particle.

Although some subjects in the study seemed to view sound transmission from a macroscopic rather than a microscopic point of view, this does not completely contradict Arons' position. The subjects in this study were in a postgraduate baccalaureate teacher training program and had already received an undergraduate degree in physics or engineering. They therefore should have been well beyond the introductory level.

Additional evidence that some students perceive sound as an entity is provided in a study by Wittmann et al. (2003). In this study subjects were asked to describe the motion of a dust particle and a candle flame placed in front of a speaker. Of the subjects interviewed prior to instruction, 45% described the dust particle and candle flame as being pushed away from the speaker. This description is consistent with the "sound as object” line of reasoning. In analyzing responses to interview questions, the authors concluded that these students:

1. “Map object-like properties onto sound waves.”
2. “Treat them as solid and pushing through a medium.”
3. “Do not correctly interpret the event-like properties that are more appropriate in this setting.”

They concluded that a focus on object-like properties such as form, location, permanence, mass, and velocity, rather than event-like properties such as location, time of occurrence, duration, and cause; was less productive in understanding wave phenomena. In the case of sound wave propagation, for example, a student’s attention might center on the velocity of sound as it travels from the source to the listener. This student would be ascribing an object-like property to sound. Another student might see sound propagation as a series of events, oscillations of the particles of the medium each with a time of occurrence and duration. This student would be paying more attention to the event-like properties of sound. The second student’s conceptualization of sound would put him or her in a much better position to describe the motion of the dust particle or the candle flame.

Hrepic et al. (2003) also found evidence that some students use an entity model for sound. They identified four properties uniquely associated with the entity model. They are:

1. “Sound is independent – sound propagates through the vacuum (does not need a medium).”
2. “Sound is material – sound is a material unit of substance and has mass.”

3. "Sound passes through empty spaces between the medium particles (seeping)."
4. "Sound is propagation of sound particles that are different from medium particles."

They also identified several models that they called hybrid models. Hybrid models contained features that were incompatible with the entity model or the community consensus model. The three hybrid models found most often in the students they interviewed were:

1. "Shaking model – Sound is a self-standing entity different from the medium, but as it propagates through the medium it causes vibration of the particles of the medium."
2. "Longitudinal shaking model – This is a special case of the shaking model where propagation of sound-entity causes longitudinal vibration of the particles of the medium."
3. "Propagating air model – Sound propagates so that air particles travel from the source to the listener."

They also found three other hybrid models, each one employed by one individual student. The models they described have many elements in common with the models identified by Linder and Erickson (1989) and Wittmann et al. (2003).

They examined student use of these models in different contexts. Students were asked about:

1. "Propagation of human voice through air and its impact on air particles."
2. "Propagation of human voice and its impact on a dust particle in the air."

3. “Propagation of a constant tone and a rhythmic, beating tone from a loud speaker and the impact of these sounds on a dust particle in the air.”
4. “Propagation of human voice through the wall at macroscopic and microscopic levels and its impact on wall particles.”
5. “. . . propagation of sound through a tight string with cans attached to its ends.”

They found that students used more than one model when answering the five questions in only two of 32 interviews. They concluded that this suggests that mental models of sound are not particularly sensitive to context. They did find a change when they interviewed students post-instruction. Several students who had used the entity model in pre-instruction interviews used hybrid models after instruction. One student who was not interviewed before instruction used the community consensus model after instruction.

In another study involving students in a teacher training program, this one for elementary teachers, Menchen & Thompson (2003, 2004) found that some students had a model for sound propagation in which the pitch of a sound depended on the material through which the sound is passing. They collected data pertaining to questions about propagation of sound through a meter stick and a metal rod. The data indicate that students who answered these questions incorrectly were unable to distinguish between propagation and resonance.

Linder (1992) found confusion caused by conflicting definitions of sound found in textbooks. The most common definition of sound relates it to “the interpretation our brains make from a range of complex eardrum movements.” At the same time, it is also directly connected to the mathematics of longitudinal waves. He also found that students have difficulty comparing and contrasting sound and light.

2.3. Curriculum Reform Efforts

Since traditional instruction has had limited success in changing students' mental models, a great deal of research has been conducted in recent years aimed at developing instructional materials that are more effective. The guiding principle behind all of these curriculum reform efforts is the belief that students must construct their own understanding of physics and that this requires their active engagement. According to McDermott (1991) "All individuals must construct their own concepts, and the knowledge they already have (or think they have) significantly affects what they can learn. The student is not viewed as a passive recipient of knowledge but rather as an active participant in its creation. Meaningful learning, which connotes the ability to interpret and use knowledge in situations not identical to those in which it was initially acquired, requires deep mental engagement by the learner. The student mind is not a blank slate on which new information can be written without regard to what is already there. If the instructor does not make a conscious effort to guide the student into making the modifications needed to incorporate new information correctly, the student may do the rearranging. In that case, the message inscribed on the slate may not be the one the instructor intended to deliver."

The need for active engagement by students has been documented by Hake (1996). In a large study of 62 introductory physics courses in which a total of 6542 students were enrolled, Hake found a significant difference between students in courses where traditional methods were used and those where substantial use of interactive engagement techniques were employed. To assess the effectiveness of various instructional methods, Hake calculated normalized gains. He defined a normalized gain as:

$$\text{Normalized Gain} = (\%\langle post\rangle - \%\langle pre\rangle)/(100 - \%\langle pre\rangle) \qquad (2.1)$$

On a test of conceptual understanding, he found a normalized gain of .48 for students in courses making use of interactive engagement techniques as compared to a normalized gain of .28 for students in courses taught using traditional methods. He also found that problem solving ability was enhanced as evidenced by students' performance on the Mechanics Baseline Test (Hestenes & Wells 1992).

McDermott (1991) has identified four principles that are characteristic of effective curriculum material:

1. "Concepts, reasoning ability, and representational skills should be developed together in a coherent body of subject matter."
2. "Physics should be taught as a process of inquiry, not as an inert body of information."
3. "The ability to make connections between the formalism of physics and real world phenomena needs to be expressly developed."
4. "Certain common difficulties that students encounter in physics need to be explicitly addressed."

Curriculum reforms that have arisen as a consequence of physics education research have taken a number of forms. Mazur (1997) developed a method of instruction that actively engages students. He called this method Peer Instruction. He assigns a pre-class reading from the text and begins each class with a short quiz over the reading material to insure that students come to class with some knowledge of the concepts that will be discussed. He divides the remainder of the class time into short segments. Each segment begins with a brief lecture or lecture demonstration followed by a multiple-choice conceptual question called a ConceptTest. Each student must answer this question individually and then discus his or her answer with several other students. During this time, each student attempts to convince their neighbors that their answer is correct.

Mazur and his colleagues found that the number of students answering these conceptual questions correctly improved substantially after the discussion. They have documented significant improvement in normalized gains on the Force Concept Inventory (Hestenes 1992) in courses taught using peer instruction at Harvard (Crouch et al. 2001). The normalized gain improved from .2 for a traditionally taught course to .5 the following year for a course incorporating peer instruction, with additional improvement in the normalized gains in succeeding years. They also found that normalized gains for a much larger number of courses at a variety of other colleges were also greater on average than the normalized gains found for traditionally taught courses (Fagen et al. 2002).

Novak (1999) created a different version of peer instruction called "Just-in-Time Teaching" or JiTT. JiTT makes use of the internet to deliver several conceptual questions in the form of a "WarmUp Exercise" that students answer on-line before coming to class. This enables the instructor to tailor lessons in such a way as to target student difficulties that are manifested in their answers to the questions on the WarmUp Exercise.

Several curriculum reform efforts involve a laboratory component. These typically make use of microcomputer-based laboratory, MBL, tools. "Tools for Scientific Thinking" is one of these. Thornton (1990) lists the following characteristics of these tools as being particularly important to student learning:

1. "The tools allow student-directed exploration but free students from most of the time consuming drudgery associated with data collection and display."
2. "The data are plotted in graphical form in real time so that students get immediate feedback and see the data in an understandable form."
3. "Because data are quickly taken and displayed, students can easily examine the consequences of a large number of changes in experimental conditions during a single laboratory period."
4. "The hardware and software tools are general – independent of the experiments."
5. "The tools dictate neither the phenomena to be investigated, the steps of the investigation, nor the level of sophistication of the curriculum."

Thornton (1990) found that students who used MBL tools developed significantly improved understanding of concepts related to velocity and acceleration compared to students taught in lecture. He found error rates as high as 40% - 60% on simple velocity questions after kinematics had been covered in lecture. Error rates fell to less than 20% following the use of MBL tools.

MBL tools have been incorporated into other curriculum reform efforts. Workshop Physics (Laws 1997) uses MBL tools for data collection within a framework of guided inquiry without any formal lectures.

Another approach involves the use of tutorials (McDermott & Shaffer 2002). The use of tutorials in teaching introductory physics was initially conceived by the Physics Education Group at the University of Washington. The collection of tutorials developed by this group has been expanded through work by researchers at other universities. Students usually begin a tutorial by taking a pretest. The pretest, often given after traditional (lecture) instruction but before the tutorial, enables the student to find out what they do and do not know about the material covered in the tutorial. They also provide the instructor with information about the level of student understanding. Students then work in groups to complete worksheets consisting of a carefully sequenced set of tasks and questions. The tutorial is followed by tutorial homework which reinforces the concepts included in the tutorial.

The effectiveness of the use of tutorials has been well documented. Among other studies, Shaffer (2005) examined the use of tutorials to improve student understanding of the vector nature of kinematics concepts. On a series of questions, Shaffer (2005) found that the percentage of students answering a question correctly improved substantially after students completed the tutorial. The percentages went from 50%, 30%, 20%, 20%, and 30% to 70%, 75%, 75%, 80%, and 65%, respectively. The post-test scores were also in line with the scores for the teaching assistants on the pretest. Shaffer (2005) considered the tutorial to be successful when the performance on the post-test matched or exceeded that of the teaching assistants on the pretest.

In another study, Cochran (2006) found that about 55% of students who had completed a tutorial on the First and Second Laws of Thermodynamics were able to correctly answer a question about a complex heat engine. That compared to a

30% – 35% correct response rate on a simpler heat engine question for students who had not completed the tutorial.

Kautz (2005) found similar results for a tutorial on the Ideal Gas Law. The percentage of students correctly answering several questions about the Ideal Gas Law was much higher for students who had completed a tutorial on the Ideal Gas Law than for students who had only received traditional instruction. On one question, 85% of the tutorial group answered the question correctly as compared to 55% of the group that had received traditional instruction. A second question yielded percentages that were closer, 50% and 40% respectively.

Additional evidence for the effectiveness of the tutorial as an instructional methodology, with examples from electric circuits and physical optics, was compiled by McDermott (2001).

Wittmann et al. (2003) examined student understanding of sound propagation. He found that prior to instruction, 9% of the students in the sample population recognized sound as a longitudinal oscillation. After a lecture on sound, this increased to 26%, and after completing a tutorial on sound, the percentage increased to 45%.

The tutorial model was adopted for use in this study. As documented previously, the use of tutorials has been shown to be effective in increasing student understanding of physics concepts. This model has been used at the University of Maine with similar results. Another important consideration was that tutorials have been used as an integral part of instruction in the course which was the focus of this study. Consequently, students participating in this study were already familiar with the concept of tutorials and the mechanics of their use. The fact that completing tutorials was viewed by students as a regular part of the course removed a variable that might have had an effect on the outcome of the study had another form of curriculum reform been chosen as an intervention.

CHAPTER 3

INTERVIEWS

The first phase of the study involved using interviews to determine the ideas that students in introductory physics classes at the University of Maine have about longitudinal waves and sound. Nine interview subjects were randomly selected from a list of approximately 30 volunteers enrolled in a section of the calculus-based introductory physics course at the University of Maine (PHY122). The class that was sampled was an off-semester class. Students were completing the second semester of the two-semester sequence in the fall of 2006 and had received instruction on waves the previous spring. The interview subjects tended to be premed and civil engineering students as opposed to mechanical or electrical engineering or physics majors. In order to preserve anonymity, each interviewee was assigned a pseudonym.

3.1. The Interview Protocol

An interview protocol was developed that assessed student thinking about wave propagation and sound. The protocol was modified twice, once after the first two students were interviewed, and a second time after the next four students were interviewed. An examination of the results of the first two interviews revealed that the interviewed subjects had limited understanding of longitudinal waves. To determine whether this lack of understanding was specific to longitudinal waves, or represented poorly formed ideas about waves in general, additional questions were added that examined student ideas about transverse waves. These questions mirrored the original longitudinal wave questions. Prior to the last three students being interviewed, three additional questions were added. For one of these questions, the interviewee was presented with a diagram of a longitudinal wave and asked for a prediction about the appearance of the wave a short time later. A second, similar question asked for a prediction about the appearance of a transverse wave a short time later. The third question asked the interviewee to describe what he or she saw when shown a diagram of a sound wave. A copy of the final interview protocol is included as Appendix A.

3.2. Identification of Mental Models for Sound Propagation

3.2.1. Results from the Radio Speaker Question

The first six questions asked during the interviews were designed to cause the interviewees to employ, and consequently reveal, the mental models that they use in analyzing situations involving the propagation of sound. The first of these questions asked how a radio speaker produces sound. The purpose of this question was to see if the interview subjects recognized that the cone of the speaker vibrates, causing the air molecules in front of the speaker to oscillate alternately toward and away from the speaker. This question was posed in the following way.

> I: I’d like to have you think about a radio speaker that is producing a sound with a constant pitch. This is a radio speaker in case you want to see what one looks like, if you haven’t seen one before. How do you think the radio speaker produces the sound that you hear?

Unfortunately, the complex nature of this device distracted the interview subjects from the intent of the question. Only two of the interviewees, Richard and Tom, seemed to have a clear idea of how a speaker operates. The following are transcripts of their answers to the first question.

Richard: There's a magnet in there. You can see the edge of it and a little coil inside. The radio unit itself sends the signal to the magnet making the coil vibrate back and forth. It has a little membrane or whatever you want to call it that vibrates that produces sound waves in the air which makes you hear it.

Tom: Well. Actually, I kind of enjoy radio speakers even though I haven't quite figured them out yet. I know that it has something to do with . . . I believe a pulse to the magnet which moves the actual speaker which causes the vibrations which you hear. How it actually does so, I'm not really sure.

Most demonstrated a familiarity with the terminology related to longitudinal waves and sound, yet were not able to provide a satisfactory explanation for the way that a speaker produces sound. Two examples of answers of this type were provided by Sarah and Mike.

Mike: I don't have much of a clue. Maybe a current comes through here and causes some type of vibration, then you have waves that resonate out.

I: You mentioned a vibration, what is vibrating?

Mike: I'm not sure – electrons maybe.

Sarah: You must get a signal from somewhere. Like I know there's a transmitter inside and it picks up the signal so you can hear it through the speaker. The waves are actually going through the speaker which go through your ear and it bounces around in you ear drum and that's how you can hear the pitch.

I: How do you think the speaker actually makes the sound?

Sarah: Must be like certain waves, certain voltages and circuits that go through the actual speaker which produces the sound. Must be wavelengths coming through the speaker which produces the certain sound that goes through the wires.

In retrospect it might have been better to ask about a simpler device, such as a tuning fork. It was not clear to the interviewees that the aspect of the speaker's operation that was important in answering this interview protocol question was the mechanical motion of the speaker cone which caused oscillation of the air molecules, not the electromagnetic interaction that converted the electrical signals to vibrations of the speaker cone. Using a tuning fork would have prevented this confusion since a tuning fork is a purely mechanical device.

3.2.2. Results from the Sound Propagation Questions

Questions Two through Four provided clearer insight into the mental models the interviewees employed while answering the questions. There were at least four distinctly different mental models that could be discerned from the answers given.

3.2.2.1. The Community Consensus Model. Two interview subjects, Richard and Julie, provided answers that indicated their mental models were in line with the community consensus model. A third interviewee, Cynthia, drew a diagram similar to the community consensus model, but did not convey in her answers to the questions that she had a clear understanding of what happens to the medium as sound is propagated.

I: Would you describe how you think the sound gets from the speaker to your ear?

Richard: That membrane I previously mentioned, it pushes the air making a little denser spot and that denser spot pushes the air molecules on and on and on and have a chain reaction until it gets to your ear which makes your ear drum vibrate and you pick it up.

I: Now I would like to have you imagine that you could see the molecules between the speaker and your ear. Do you think that the air molecules move?

Richard: Kind of, not really. They move back and forth but don't actually move from the speaker to my ear.

I: So they don't move a long distance?

Richard: Right, they just kind of vibrate.

Richard was also able to produce a reasonable representation of the distribution of the air molecules in the path between the speaker and the ear while the speaker is producing a tone with a constant pitch. His diagram is shown as Figure 3.1.

Figure 3.1. Richard's diagram of a sound wave.

Julie answered these questions in the following way.

I: Would you describe how you think the sound gets from the speaker to your ear?

Julie: There are particles in the air that vibrate and they vibrate into your ear and your ear drum vibrates and you hear them.

I: Can you describe that a little bit more?

Julie: Like the radio produces the wave and as the wave goes through the particles it vibrates each particle and each particle vibrates the next particle and so on and so on until it reaches your ear.

I: Imagine that you could see the air molecules in the path between the speaker and you ear. Do you think the air molecules move?

Julie: Yes.

I: Can you describe the motion of one of the air molecules as the sound from the speaker passes?

Julie: It would be like back and forth (moves hand from side to side) like they are vibrating.

I: By back and forth do you mean in the same direction as the sound is traveling, or perpendicular to it, or in some other direction?

Julie: As the same direction as the sound.

Unlike Richard's diagram, Julie's did not show any variation in the spacing of the air molecules. Her diagram is reproduced as Figure 3.2.

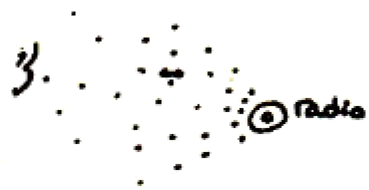

Figure 3.2. Julie's diagram of a sound wave.

Another interviewee, Cynthia, was also able to draw a reasonably accurate diagram. Her diagram is reproduced as Figure 3.3.

Figure 3.3. Cynthia's diagram of a sound wave.

She was not, however, able to give a good description of what was happening.

I: Would you describe how you think the sound gets from the speaker to your ear?

Cynthia: Through sound waves in the air.

I: Can you expand on that?

Cynthia: I'm trying to remember. I'm pretty sure they're called longitudinal waves, but they're different from the kind of . . like the wave function kind of wave I think. Gosh, I can't really . . . I know that . . I don't know. I don't know. I give up.

I: I'd like to have you imagine you could see the air molecules in the path between the speaker and your ear. Do you think the air molecules move?

Cynthia: I know that they get more compressed and more expanded. I don't think that they actually move.

I: How do you think they get more compressed and more expanded?

Cynthia: I guess by the pressure produced by whatever's making the sound.

3.2.2.2. The Flowing Air Entity Model. Answers by two of the interviewees, Rita and Sarah, provided evidence that they were employing an entity mental model. Their answers indicated that they pictured sound as passing through the air and pushing the air molecules out of the way. This corresponds to one of the models described by Linder (1992). It will be referred to as the "flowing air" model.

I: Would you describe how you think the sound gets from the speaker to your ear?

Rita: Through the medium that it's going through. I remember last semester we talked about how the vibrations reach into the inner part of your ear and different tones cause you to hear what you are listening to. I don't really remember discussing how it happens.

I: I'd like to have you imagine you could see the air molecules in the path between the speaker and your ear when the speaker is producing a sound with a constant pitch. Would you describe the motion of one of those air molecules as the sound is passing by?

Rita: It probably bounces away from where its normal position would have been due to the sound passing through it, through that area.

I: So it would move, and move how?

Rita: I guess it would move relative to – probably I would guess some sort of like proportional like at an angle off of the sound waves that are being created by the speaker.

I: Would it move in the same direction that the sound is going, the opposite direction?

Rita: Perpendicular.

I: Perpendicular to the direction the sound is going?

Rita: Yeah, I think so.

Rita's diagram consisted of a series of curved lines that she referred to as the sound wave, with dots that represented air molecules being pushed aside and forward. Rita's mental model was similar to the entity model for sound described by Linder (1992) or the "sound as object" model documented by Wittmann et al. (2003). The diagram that Rita drew is shown as Figure 3.4.

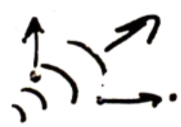

Figure 3.4. Rita's diagram of a sound wave.

Sarah's diagram was similar to Rita's. Her answers to the questions also showed that she was using an entity model as her mental model for sound.

I: Can you describe how you think the sound gets from the speaker to your ear?

Sarah: I sort of answered that but not really. It's the wavelengths from the speaker that are going, that are just bouncing off the walls and it catches in your ear and your ear drum catches the wavelengths, the different sized wavelengths depending on how loud or the certain pitch it is.

I: I'd like to have you imagine that you could see the air molecules in the path between the speaker and your ear. Do you think the air molecules move?

Sarah: I think they would because there's the wave in the air molecules and the wave is pushing the air molecules. Maybe not all of them, but most of them.

I: Can you describe the motion of one of the air molecules as the sound from the speaker is passing?

Sarah: It's probably not moving with the wavelength, but off to the side or either side.

I: So it would be moving up and down?

Sarah: Or just away from it. Like maybe it would bounce off.

3.2.2.3. The Stationary Particle Entity Model. Answers by Tom and Steve provided evidence that they were employing another form of entity mental model. Their answers indicated that they pictured sound as passing through the air without disturbing the molecules of air. This model will be referred to as the "stationary particle" model.

Tom's mental model was similar in some respects to those of Rita and Sarah in that sound was pictured as an entity that passed through the medium. In Tom's model, however, only the air molecules near the speaker moved. Air molecules further from the speaker remained stationary as the sound passed through them.

I: Can you describe to me how you think the sound gets from the speaker to your ear?

Tom: It's transferred by waves just to your ear where your ear receives the waves and decodes them.

I: Can you expand upon that?

Tom: The frequency is projected and it travels as far as it can before it fades out and if it reaches your ear before it fades out your ear is designed to take that and translate the pitch, tone, frequency, everything and figure out what it means.

I: I'd like to have you imagine that you could see the air molecules in the path between the speaker and your ear. Do you think that the air molecules move?

Tom: I think they move. They move initially obviously because the speaker has to move and once it's producing the sound I don't know if they move or not. I'm going to say they don't move once it's at a constant pitch.

I: So initially they start to move? Can you describe how they'd move?

Tom: It would depend on the sound the speaker's producing. Either the speaker is going to go out which will cause them to move away from the speaker or it'll be brought back in which will suck them in but either way it's not over a very large distance that the molecules are moving.

I: After they move initially then they stop?

Tom: Yeah.

I: They don't move any more?

Tom: Yeah, they realign themselves or however you want to put that to the new area which they have and settle down if it's producing a constant pitch.

Tom's diagram, (shown as Figure 3.5) had air molecules close to the speaker spaced farther apart and molecules farther from the speaker spaced closer together.

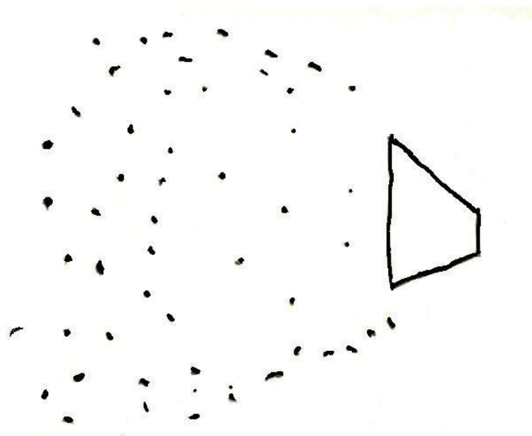

Figure 3.5. Tom's diagram of a sound wave.

Steve also stated that he did not think that the air molecules moved, but drew a diagram showing a series of dots arranged in the form of a transverse wave. His answers to the questions suggested that he was using the stationary particle entity model for sound.

I: Can you describe how you think the sound gets from the speaker to your ear?

Steve: I think wavelengths and then something in the air. There's a . . . can sense pressure or something. I'm not exactly sure how it works. But the waves oscillate different frequencies making different noises I guess. I don't know what else to call them. I think it sends it through the air and it reaches your ear and it picks up on that. I think it oscillates something in your ear drum. I'm not sure what though. I'm guessing though.

I: How do you think that the sound gets from one place to another?

Steve: Changes in air pressure, I'm not sure. I have no idea.

I: Imagine that you could see the air molecules in the path between the speaker and your ear. Do you think that the air molecules move?

Steve: No.

I: So they are just stationary?

Steve: Just stationary, yeah.

Steve's diagram for a sound wave can be seen in Figure 3.6.

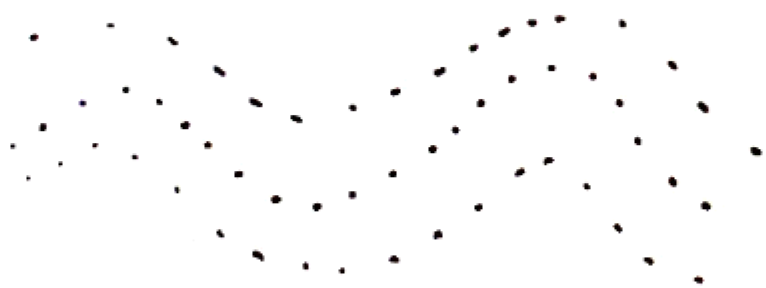

Figure 3.6. Steve's diagram of a sound wave.

3.2.2.4. The Hybrid Transverse/Longitudinal Model. Evidence for a fourth mental model was provided by Ralph and Mike. This is one that Hrepic (2002) described as a hybrid model. In this model, the air molecules are perceived as oscillating perpendicular to the direction of propagation, so it represents a merging of ideas about longitudinal and transverse waves. As can be seen from the following transcript excerpts, the mental models employed by these interview subjects include aspects of the entity model.

I: I'd like to have you describe how you think the sound gets from the speaker to your ear.

Mike: It's a sound wave vibration in the air that reaches your ear. It's picked up in your ear by the bones and you get the signal through your brain.

I: Can you explain a little bit more by what you mean by "vibration in the air?"

Mike: Energy that moves. I guess, I don't know how to say, more than just vibrates but just travels through the air, moves the surrounding air and just reaches your ear, maybe.

I: What is it you think is vibrating?

Mike: I don't know, just energy. I just imagine energy traveling. That's really all I can explain.

I: I'd like to have you imagine that you could see the air molecules in the path between the speaker and your ear. Do you think the air molecules move?

Mike: I imagine them to. I don't know if they don't, but I do I do imagine them to.

I: Could you describe the motion of one of those air molecules as the sound from the speaker passes?

Mike: It just oscillates like that (moves hand up and down) goes up and down.

I: Can you tell me which way the sound is going?

Mike: If it goes that way (moves hand from right to left) and the molecules go up and down (moves hand up and down).

I: So the molecules are moving perpendicular to the direction the sound is traveling in?

Mike: Yes.

Mike drew a diagram (shown in Figure 3.7) consisting of a series of dots that formed a transverse wave and indicated that each particle would move perpendicular to the axis of the wave.

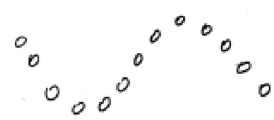

Figure 3.7. Mike's diagram of a sound wave.

The answers that Ralph gave indicated that his mental model was not as well formed as Mike's, or at least not as well articulated.

I: I'd like to have you describe how you think that sound gets from the speaker to your ear.

Ralph: Well, it travels in waves at a certain frequency and your ear responds to that frequency and picks up the frequency if it can.

I: Can you describe a little bit more about what you mean by traveling in waves?

Ralph: Well sound travels in a wave that has a certain wavelength and frequency. Those two are connected. I believe that if you multiplied them you get the speed of light so there is an inverse relationship there.

I: I'd like to have you imagine that you could see the air molecules in the path between the speaker and your ear when the speaker is producing a sound with a constant pitch. I'd like to have you describe the motion of one of those air molecules as the sound from the speaker passes by.

Ralph: I would think it would be vibrating at whatever the frequency of the sound is.

I: What do you mean by vibrating?

Ralph: Moving back and forth as the waves pass through.

I: In what way – in the same direction as the sound is moving, perpendicular?

Ralph: Perpendicular.

Ralph was not able to draw a diagram of a snapshot of a sound wave.

3.3. Ideas about Transverse Wave Propagation

Seven of the interview subjects were asked questions about transverse waves for comparison purposes. The interviewees were asked to imagine a long slinky with someone shaking one end from side to side, and asked to describe the motion of one of the coils of the slinky. All were able to correctly recognize that the coil oscillates perpendicular to the direction of propagation of the wave. All were also able to draw a representation of the slinky as either a sine curve or a decaying sine curve. Steve's diagram (Figure 3.8) is representative of the sine curve diagrams drawn by students. Tom's diagram (Figure 3.9) is representative of the decaying sine curve diagrams drawn by students.

Figure 3.8. Steve's diagram of a slinky.

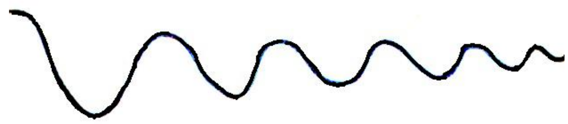

Figure 3.9. Tom's diagram of a slinky.

3.4. Ideas about the Motion of Air Molecules During Sound Wave Propagation

The ability to answer interview protocol questions 7 through 13 depended to a large extent on being able to recognize that, when sound is propagated through air, air molecules oscillate parallel to the direction of oscillation. Only three interview subjects provided evidence that they used this idea as their mental model in the answers they gave to questions and in the diagrams that they drew. These three interviewees, as previously identified, were Julie, Cynthia, and Richard.

Each interviewee was given a copy of the diagram shown as Figure 3.10. They were asked to mark places where the pressure was higher than normal atmospheric pressure with an arrow and the letter H, and to mark the places where the pressure was lower than normal atmospheric pressure with an arrow and the letter L. Similarly, they were asked to mark places where the air molecules were moving the fastest and the slowest, and where the air molecules had the maximum and the minimum displacements from their equilibrium positions.

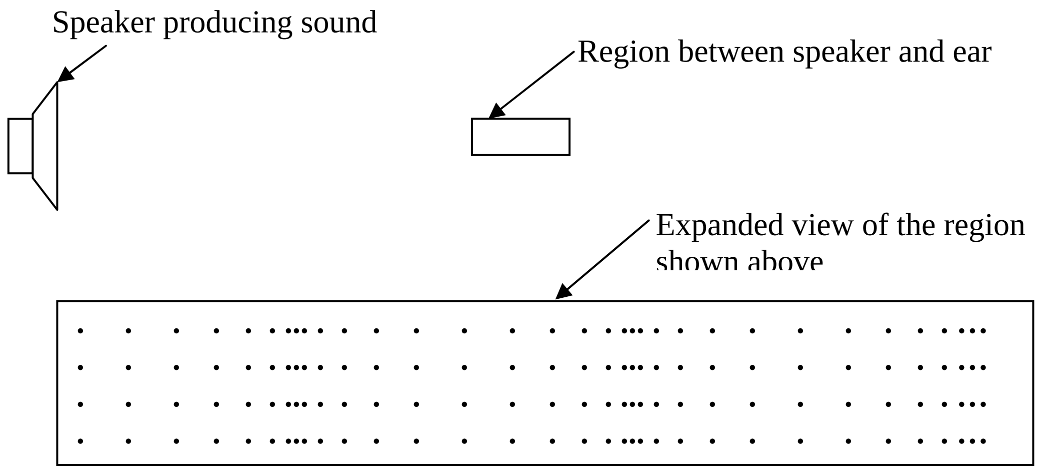

Figure 3.10. Diagram of a sound wave used for interview questions 5 through 13.

3.4.1. Identifying Compressions and Rarefactions

When asked about the locations of the relative high and low pressure areas, Julie focused on the fact that sound is attenuated as it travels through the medium and predicted that the pressure would be higher than normal atmospheric pressure near the speaker and lower than atmospheric pressure far from the speaker.

Both Cynthia and Richard correctly identified places where the dots on the diagram were closely spaced as being points of relatively high pressure and places where the dots were widely spaced as being points of relatively low pressure.

Two other interviewees also correctly identified the location of the high and low pressure areas, Rita and Mike. Ralph correctly identified the high pressure areas, but was not able to decide if there were any areas where the pressure was lower than normal atmospheric pressure.

Sarah used the same reasoning that Julie used, identifying areas close to the speaker as representing regions of high pressure and areas far from the speaker as representing regions of low pressure. Steve predicted that the horizontal row of dots centered on the speaker was the region of high pressure and the top and bottom rows of dots were the regions of low pressure. Tom thought that the pressure would be the same everywhere.

These results were somewhat surprising. An inability to interpret the diagram may have been one factor that caused students difficulty when answering these questions. Tom, for example, when asked what he saw when he looked at the diagram gave the following answer:

> I: This is a diagram that might have been drawn representing a snapshot of the air molecules as a sound wave passes by. The dots represent air molecules. What do you see when you look at this diagram?
>
> Tom: Well, if these are air molecules they aren't moving at all and they're all evenly distributed.

Tom evidently did not recognize that some of the dots were intentionally drawn closer together and others farther apart. This is consistent with his model for sound propagation in which sound passes through the medium without disturbing the particles. He seems to hold a belief in this model so firmly that he sees the variation in the spacing of the dots in the diagram as irrelevant.

There also seemed to be confusion between the temporal and the spatial. It is true that, at a given point in time, points close to the speaker where the particles are close together represent areas where the pressure is higher than points far from the speaker where the particles are also close together (spatial). But the spacing between the particles changes with time (temporal) and a point near the speaker that corresponds to a place of high pressure at one point in time will correspond to a place of low pressure a short time later. The answers given by interview subjects that focused on the attenuation of the sound are indicative of a failure to make this connection. It might also be interpreted in terms of the "object-like" properties and "event-like" properties described by Wittmann et al. (2003). Students who concentrated on the attenuation of the sound were focusing on an "object-like" property; a line of reasoning that is less useful in analyzing sound propagation.

3.4.2. Predictions about Molecule Speeds

None of the interview subjects were able to answer both questions 9 and 10 in the interview protocol, which asked students to predict the maximum and minimum particle speeds. Only one interview subject, Richard, used reasoning that might have resulted in correct answers. Richard used the fact that the air molecules were undergoing simple harmonic motion. He mistakenly predicted that an air molecule located halfway between a compression and a rarefaction, corresponded to a mass on a spring that was passing through its equilibrium position. His answers to these two questions were therefore the reverse of the correct answers.

I: How did you decide where to draw those?

Richard: Cause last semester in simple harmonic motion which is pretty much what this is we learned that at the lowest point when something is swinging or springs going back and forth it'll be moving the fastest and at the highest point it's moving the slowest.

Two interview subjects, Rita and Cynthia, identified the air molecules in the regions of closely spaced dots as moving the fastest, but incorrectly identified air molecules in regions of widely spaced dots as having minimum speed.

One interview subject, Ralph, was able to correctly identify regions between closely spaced dots and widely spaced dots as areas where the air molecules had minimum speed, but he was unable to identify any areas where the air molecules would have maximum speed.

All of the other interviewees answered both questions incorrectly. Consequently, out of a total of nine interview subjects, only one thought about these questions in a way that was similar to the way an expert in the field might think about them, and he still was unable to arrive at the correct answers. Table 3.1 summarizes the ideas that the interviewees expressed concerning the points in the sound wave where the particle speeds have maximum and minimum values.

Model	**Interviewee**	**Maximum Speed**	**Minimum Speed**
Community Consensus	Richard	Equilibrium Pressure	Compress./Rarefact.
	Cynthia	Compressions	Rarefactions
	Julie	Near speaker	Far from speaker
Flowing Air (Entity)	Rita	Compressions	Rarefactions
	Sarah	Near speaker	Far from speaker
Stationary Particle (Entity)	Tom	Near speaker	Far from speaker
	Steve	Along speaker axis	Above/below axis
Hybrid	Mike	Equilibrium Pressure	Compress./Rarefact.
	Ralph	All speeds the same	Equilibrium Pressure

Table 3.1. Summary of particle speed interview protocol questions.

3.4.3. Predictions about Molecule Displacements

Interview protocol questions 11 and 12, which asked students to predict the maximum and minimum particle displacements, produced similar results. Richard's answers to these two questions were again the reverse of the correct answers. All of the other interview subjects' answers for both questions were incorrect.

As mentioned previously, one idea that caused confusion stemmed from paying too much attention to the attenuation of sound as it propagates. Sarah, Julie, and Tom all predicted that an air molecule close to the speaker would have a maximum magnitude of displacement from its equilibrium position and an air molecule far from the speaker would have a minimum magnitude of its displacement.

A second source of confusion arose from the fact that it is possible to identify two distinct equilibrium positions. Questions 11 and 12 asked about displacement from the position that the air molecule would occupy if no sound was present. Maximum displacement in that case would correspond to points of normal atmospheric pressure and minimum displacement would correspond to the centers of the compressions and rarefactions. It is also possible to view the diagram from the standpoint of pressure equilibrium. In this view, the positions of normal atmospheric pressure, the pressure equilibrium positions, are halfway between the compressions and rarefactions. An air molecule located at the pressure equilibrium position would be located a minimum distance from this pressure equilibrium position. Air molecules located at the centers of the compressions and rarefactions would be located a maximum distance from a pressure equilibrium position. Two of the interview subjects, Ralph and Mike answered in this way. The interview questions were posed in the following way:

I: Would you draw arrows on the diagram that point toward places in the diagram that represent areas where the molecules have the maximum displacement from their equilibrium position, if there are any, and label the arrows Max. Explain how you decided where to draw the arrows.

I: Would you draw arrows on the diagram that point toward places in the diagram that represent areas where the molecules have the minimum displacement from their equilibrium position, if there are any, and label the arrows Min. Explain how you decided where to draw the arrows.

Ralph: The max is kind of just a guess. I thought it would be the low pressure areas and the high pressure areas.

Ralph: Between the high and the low pressure areas since that's where the pressure would be closest to normal.

Mike: Points where the pressure is highest and lowest is where they would have the maximum displacement.

Mike: Places halfway between highest and lowest pressure.

One other, Rita, chose only the closely spaced dots for the maximum displacement, not the widely spaced dots, and half way between the closely spaced dots and the widely spaced dots as the points of minimum displacement.

Rita: Closer to where the high pressure is.

Rita: In the middle between the high and the low.

Table 3.2 summarizes the ideas that the interviewees expressed concerning the points in the sound wave where the magnitude of a particle's displacement from its equilibrium position has a maximum value and where it has a minimum value.

Model	Interviewee	Max. Displacement	Min. Displacement
Community Consensus	Richard	Compress./Rarefact.	Equilibrium Pressure
	Cynthia	Compressions	Rarefactions
	Julie	Near speaker	Far from speaker
Flowing Air (Entity)	Rita	Compressions	Equilibrium Pressure
	Sarah	Near speaker	Far from speaker
Stationary Particle (Entity)	Tom	Near speaker	Far from speaker
	Steve	Along speaker axis	Above/below axis
Hybrid	Mike	Compress./Rarefact.	Equilibrium Pressure
	Ralph	Compress./Rarefact.	Equilibrium Pressure

Table 3.2. Summary of particle displacement interview protocol questions.

3.4.4. Predictions about Wavelength

A number of the interview subjects had difficulty identifying one wavelength on the diagram. Five interviewees, Rita, Mike, Sarah, Cynthia, and Richard, were able to do this correctly. Sarah, however, was unsure of her diagram and thought that it was necessary to know the frequency to be able to correctly identify one wavelength. Ralph marked a wavelength on the diagram as extending from the left hand side of the diagram to the right hand side. He considered marking a wavelength as extending from one region of closely spaced dots to the next, but was not sure that this was correct.

Two interviewees, Julie and Tom, focused on the individual dots themselves. Julie drew a wavelength as extending from one dot to the next. Tom drew the wavelength as extending from one dot, skipping three dots, to the fourth dot. Steve was unable to make marks on the diagram that corresponded to the end points of one wavelength. He thought that it was necessary to know the frequency in order to be able to figure out the wavelength.

3.5. Ideas about the Motion of Slinky Coils During Transverse Wave Propagation

The interview subjects were in a somewhat better position when asked to answer questions about the motion of the coils of a slinky as a transverse traveling wave propagated along its length.

3.51. Predictions about Slinky Coil Displacements

All of the interviewees with the exception of Tom identified the crests and troughs on a diagram (Figure 3.11) as the points of maximum displacement from the equilibrium position and the midpoints between crests and troughs as the points of minimum displacement.

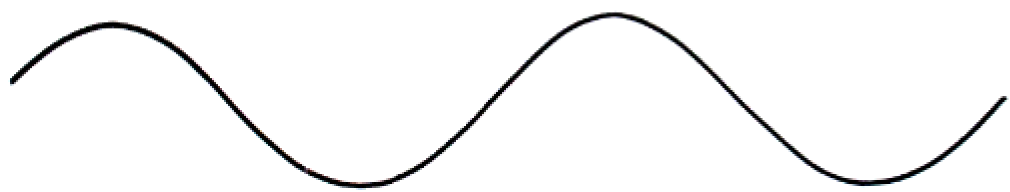

Figure 3.11. Diagram of a transverse wave on a slinky.

Tom indicated that points close to the left-hand end of the slinky would have the maximum displacement and points close to the right-hand end would have the minimum displacement. As with his answer to the related question about a longitudinal wave, the idea that the wave would be attenuated as it was propagated triggered this response.

3.5.2. Predictions about Slinky Coil Speeds

Answers to interview protocol questions 16 and 18 were more varied. Only two interview subjects, Mike and Julie, correctly identified the midpoints between crests and troughs as the points where the coils move the fastest and the crests and troughs as the points where the coils move the slowest. Once again, Tom focused on the attenuation during propagation and predicted that the coils closest to the left-hand end would be moving the fastest and coils closest to the right-hand end would be moving the slowest.

All of the other interviewees that were asked this question reversed the answers, identifying both the crests and troughs as the points of maximum speed. Prior experiences observing standing waves probably lead them to this conclusion. When a slinky is used to demonstrate transverse waves it is more often used to demonstrate standing waves than to demonstrate traveling waves. In a standing wave, the midpoints between the crests and the troughs are nodes and there is no motion of the coils at these points. The maximum coil speed occurs at the antinodes, but only when the coil is passing through the equilibrium position, not when it is in the position shown in the diagram.

CHAPTER 4

CURRICULUM REFORM

4.1. The Nature of the Reform Effort

The second phase of this study documented the effect of utilizing a research based instructional methodology on student understanding of the propagation of longitudinal waves and sound. Results from interviewing students in the PHY 122 class showed that there was a significant discrepancy between the answers to the interview questions that the interviewees provided, and the corresponding community consensus answers. This was interpreted as evidence that these students either did not have well formed mental models for the propagation of sound, or that their mental models required significant alteration to bring them in line with the community consensus model. The fact that traditional instruction had not led to the development of mental models that would enable students to answer the interview questions correctly indicated that a different instructional approach was needed. The approach taken was the development of a tutorial along the lines of the tutorials created by the Physics Education Group at the University of Washington. This method was selected from among the several validated research-based curriculum reform efforts primarily because similar tutorials are used as an integral component of the target course for this study, the introductory algebra-based physics course at the University of Maine (PHY 112). Students in this class are comfortable with the rationale for using tutorials and the mechanics of completing them.

Two hours each week are usually reserved for working on tutorials in PHY 112. The tutorial developed for this study required portions of two 50-minute class sessions to complete. The tutorial was started a week prior to an exam being given and was completed just before the exam was given in some cases and just after the exam was given in others. To determine the effect that the use of the tutorial had on student understanding of the propagation of longitudinal waves and sound, a pretest and a post-test were administered and the results analyzed. The pretest was administered after traditional instruction on waves. The post-test was administered within two weeks of the completion of the tutorial.

4.2. The Pretest

The pretest consisted of six multiple-choice questions. The first two questions probed the general mental models that students used to analyze situations involving the nature and propagation of sound waves. The results from the interviews indicated that the interviewees each utilized one of four mental models related to sound propagation. In addition to the community consensus model of particles oscillating parallel to the direction of propagation, some students described particles oscillating perpendicular to the direction of propagation (the hybrid model), some students described the particles as being pushed away from the path of the sound (the flowing air model), and some students pictured the particles as remaining stationary as the sound passed by (the stationary particle model). The first two questions on the pretest asked students to choose from among these models to explain how a radio speaker produces sound and how sound is propagated.

The remaining four questions asked students about the behavior of air molecules as sound is propagated. Students were presented with the diagram shown in Figure 4.1.

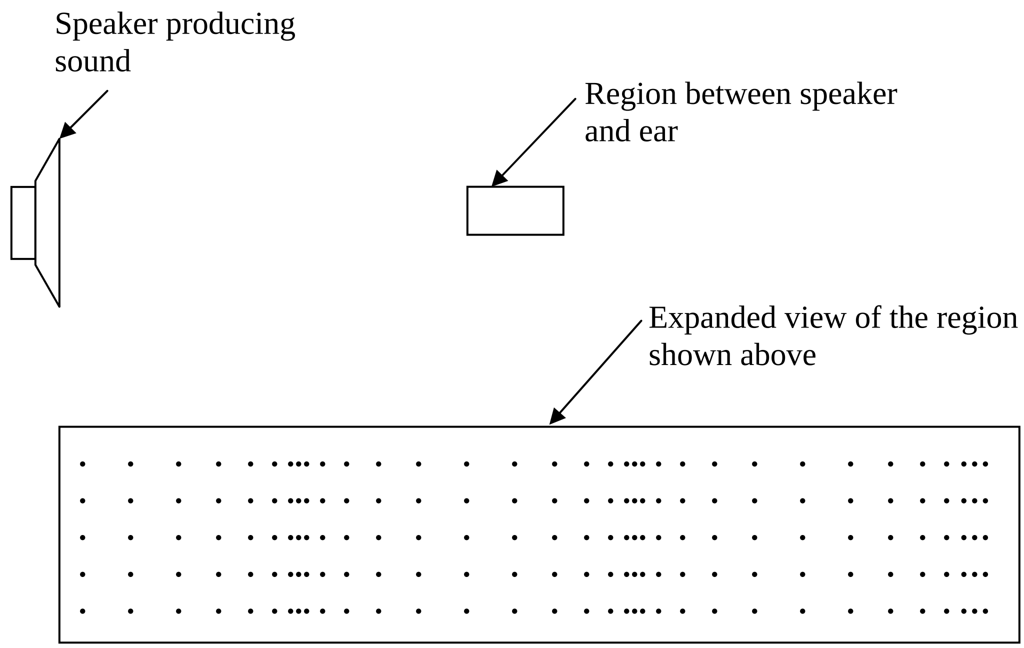

Figure 4.1. Diagram of a sound wave used for pretest and post-test questions.

They were asked to identify regions on the diagram where the pressure was higher than normal atmospheric pressure, where the air molecules were moving fastest, where the air molecules were displaced from their equilibrium positions by a maximum amount and where the air molecules were displaced by a minimum amount. Since the students who were given the pretest had previously enrolled in PHY 111, the prerequisite course for PHY 112, and had therefore encountered the gas laws, it was expected that they would be able to identify regions where the dots were close together as areas where the pressure was higher than normal atmospheric pressure, and regions where the dots were farthest apart as areas where the pressure was lower than normal atmospheric pressure. It was also anticipated that students would be able to make use of their knowledge of longitudinal waves, a topic covered in PHY 112 prior to administration of the pretest, and their knowledge of simple harmonic motion to predict the locations where the velocity of the particles and the displacement of the particles from their equilibrium positions have maximum and minimum magnitudes.

Students were asked to indicate their choices by selecting from a number of pre-defined areas on the lettered diagrams shown in Figure 4.2. These regions were selected because they matched the responses given by the interview subjects.

A copy of the entire pretest can be found as Appendix C.

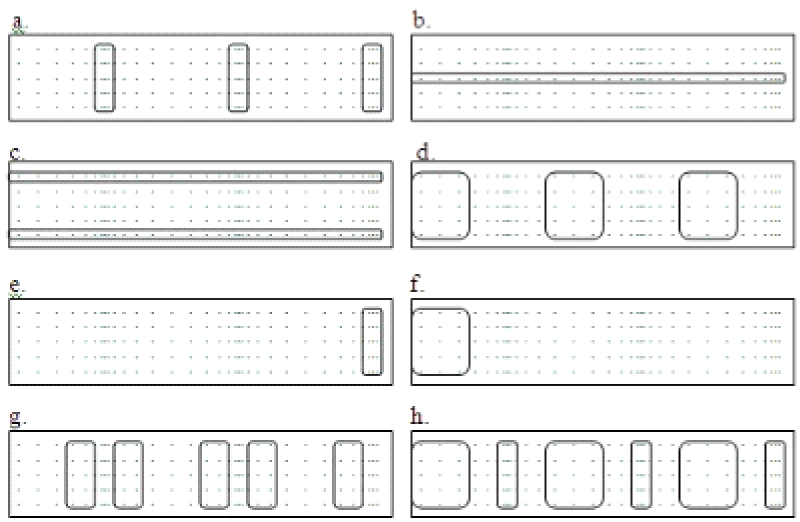

Figure 4.2. Regions from which students could choose when answering pretest questions.

The class on which this study was based had 76 registered students. Due to an oversight, the pretest was administered in two parts. The first four questions were administered on one day and the last two questions on another day. As a consequence of this and absenteeism on one day or the other, only 38 students completed the entire pretest.

4.3. The Post-test

The post-test consisted of six questions. The first question was multiple-choice and similar to the second question on the pretest. This question evaluated the general mental models students used to analyze situations related to the nature and propagation of sound waves. The next four questions were of the multiple-choice-multiple-response variety so that the questions on the post-test would not be identical to the questions on the pretest. These questions corresponded to the last four questions on the pretest. They specifically addressed the behavior of air molecules as sound is being propagated. As in the pretest, students were presented with the diagram of a sound wave shown in Figure 4.1. This time they were asked to indicate their answers by selecting lettered regions on the diagram shown in Figure 4.3. They were asked to mark all regions that matched the criterion specified in the question.

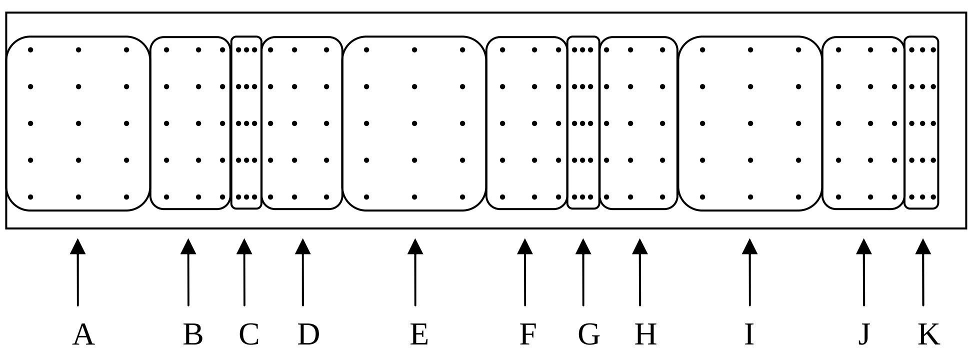

Figure 4.3. Regions from which students could choose when answering post-test questions.

The last question presented students with a diagram that represented a portion of a sound wave and asked them to sketch a snapshot of the air molecules in this region a short time later. A copy of the complete post-test can be found as Appendix D.

The subset of the student population that took the post-test was not the same as the subset that took the pretest. Forty-six students completed the post-test. Not all of these students had completed both parts of the pretest. A total of 33 students completed both parts of the pretest and the post-test. The matched pretest and post-test results from these students were used to evaluate the effectiveness of the tutorial.

4.4. The Tutorial

4.4.1. Overview of the Tutorial

The tutorial that was developed (see Appendix E) had four major components. Both the interviews and the pretest demonstrated that a significant number of students did not have a mental model for the propagation of sound that was consistent with the community consensus model, oscillation of the particles of the medium parallel to the direction of propagation. The first section of the tutorial was designed to address this.

Evidence from the interviews also showed that students were unable to predict the behavior of the particles of the medium during longitudinal wave propagation. None of the students interviewed had a mental model that enabled them to consistently make correct predictions about the behavior of the particles of the medium. The second and third portions of the tutorial were designed to address this deficiency by introducing a simple harmonic motion mental model that could be used to analyze the behavior of the particles of the medium. In the second part of the tutorial, students reviewed simple harmonic motion. In the third part of the tutorial, students were asked to apply their knowledge of simple harmonic motion to the motions of a number of masses separated by springs. This arrangement of masses and springs served as a model for the particles of the medium through which a longitudinal wave is propagating.

The last part of the tutorial required students to use the information they had obtained from the simple harmonic motion model for longitudinal wave propagation to predict the behavior of air molecules through which sound is propagating.

4.4.2. Part I: Propagation of Sound and its Effect on the Medium

The first part of the tutorial was modeled after the tutorial created by Wittmann et al. (2003). However, instead of viewing a video clip of candle flame in front of a speaker, students observed a video clip of a soap bubble in front of a speaker. This section of the tutorial was critical because it was essential that students have an accurate mental model for sound wave propagation before they began making predictions about the behavior of the particles of the medium.

Students were presented with a dialogue among four students. The first student postulated the stationary particle model in which sound passes through the medium without affecting the particles of the medium. The second student was a proponent of the hybrid transverse/longitudinal model in which the particles of the medium oscillate perpendicular to the direction of propagation. The third student held the consensus view that the particles of the medium oscillate parallel to the direction of propagation. The fourth student expressed a belief that the particles of the medium must travel from the source to the ear in order for a sound to be heard. This represented the flowing air model. These were the four most common mental models expressed in the interviews and pretest question answers.

Students were next asked to use each model to describe the motion of a soap bubble in front of a speaker that was producing a sound with a low constant pitch. Students then watched a video clip of a soap bubble and were asked to evaluate the models on the basis of their observations. Figure 4.4 is one frame from the video clip of the soap bubble in front of the speaker.

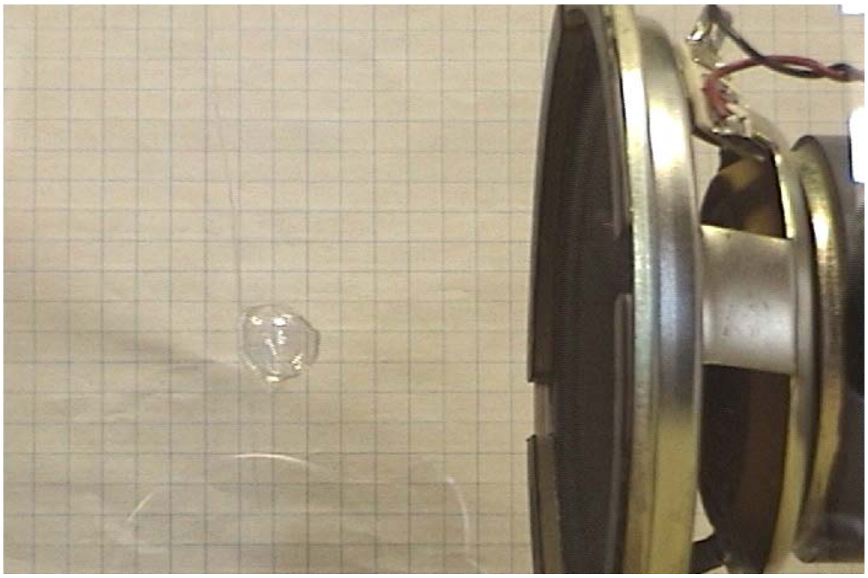

Figure 4.4. The first frame from the soap bubble in front of the speaker video clip.

4.4.3. Part II: Characteristics of Simple Harmonic Motion

Students in PHY112 are expected to be familiar with simple harmonic motion since it is a topic that is covered in the prerequisite course, PHY111. In the second part of the tutorial the behavior of a particle undergoing simple harmonic motion was reviewed.

Students were asked to examine the motion of a mass between two springs undergoing simple harmonic motion by viewing an animation of the object, and to draw free body diagrams for the mass in various positions. Figure 4.5 is one frame of this video clip.

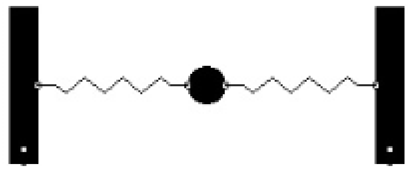

Figure 4.5. Mass oscillating between two springs.

Using the free body diagrams, students were asked to predict the points where the net force on the mass had a maximum magnitude and where it had a minimum magnitude. It was expected that students could determine this from the relative extensions and/or compressions of the springs on either side of the mass. Students were then asked to make use of the information about the net force to predict the points where the magnitudes of the acceleration, velocity, and displacement from the equilibrium position had maximum and minimum values.

According to Newton's Second Law:

$$\Sigma F = ma \tag{4.1}$$

The acceleration is proportion to the net force and has maximum values where the net force has maximum values.

For an object undergoing simple harmonic motion, the mass is subject to a restoring force that is proportional to the displacement of the object from its equilibrium position.

$$F = -kx \tag{4.2}$$

Since the acceleration is the second derivative of the displacement, this equation can be written as:

$$m\frac{d^2x}{dt^2} = -kx \tag{4.3}$$

The solution of this differential equation is well known and has the form:

$$x = ASin(\sqrt{\frac{k}{m}}t + \phi_o) \tag{4.4}$$

The velocity of the mass is the first derivative of this function:

$$v = A\sqrt{\frac{k}{m}}Cos(\sqrt{\frac{k}{m}}t + \phi_o) \tag{4.5}$$

The acceleration is the second derivative of the function:

$$a = -A\frac{k}{m}Sin(\sqrt{\frac{k}{m}}t + \phi_o) \tag{4.6}$$

The solution contains two arbitrary constants, A and ϕ_o that can be determined from initial conditions.

Students using the tutorial were not asked to derive these equations; in fact, this would probably have been beyond their mathematical capabilities. It was only necessary for them to recognize the relationships among the mass's displacement from its equilibrium position, its velocity, and its acceleration. When the magnitude of the force on the mass is a maximum, the magnitudes of its acceleration and displacement are also maxima and the magnitude of its velocity is a minimum (zero). When the magnitude of the force on the mass is a minimum (zero), the magnitude of its acceleration and displacement are also minima (zero) and the magnitude of its velocity is a maximum.

4.4.4. Part III: A Simple Harmonic Motion Model for Longitudinal Waves

In the third part of the tutorial students were asked to use their knowledge of simple harmonic motion as a bridge to enable them to understand of the more complex behavior of the particles of a medium during longitudinal wave propagation. In this part of the tutorial, students were asked to view a video clip of a simulated longitudinal wave made up of several masses connected by springs. Several snapshots of this simulated longitudinal wave are shown in Figure 4.6.

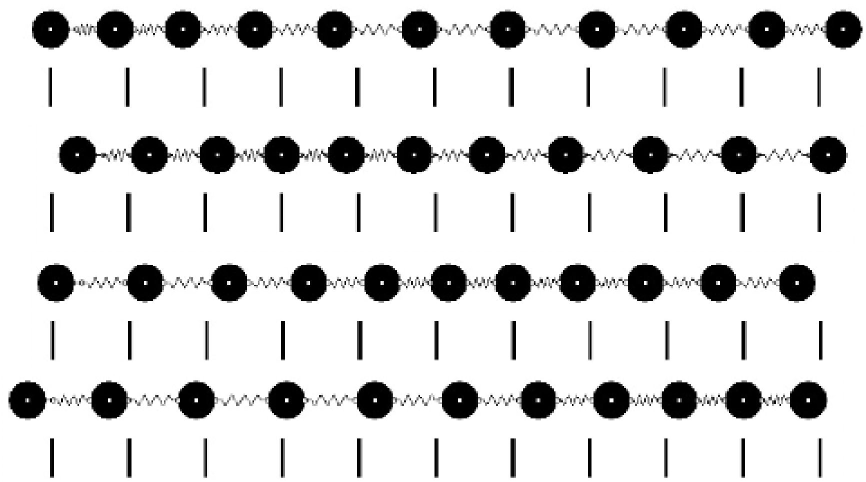

Figure 4.6. Four frames from the video clip of a simulated longitudinal wave.

Students were asked to carefully observe the motion of one of the masses and, based on the relative compression and/or extension of the springs on either side; predict the net force on the mass and the magnitudes of its acceleration and velocity when it is located at its equilibrium position. The vertical lines served as reference points to mark the locations of the equilibrium positions of the masses. From a careful analysis of the video clip, it is possible to recognize that the net force on the mass, and therefore its acceleration is zero when it is at its equilibrium position, and that its velocity has a maximum magnitude at that point. By observing the spacing of the masses around one that is located at its equilibrium position, it is possible to see that the mass is at its equilibrium position when it is at the center of a compression or a rarefaction.

4.4.5. Part IV: Applying the Simple Harmonic Motion Model to Sound

The last part of the tutorial asked students to apply what they discovered about the simulated longitudinal wave to sound. Students were presented with a diagram depicting a snapshot of a section of a sound wave (Figure 3.1). Students were then asked to identify regions where the pressure is higher than normal atmospheric pressure and regions where it is lower. They were also asked to identify regions where the air molecules are displaced from their equilibrium positions by a maximum amount and where they are displaced by a minimum amount, as well as to identify regions were the air molecules are moving the fastest and where they are moving the slowest.

CHAPTER 5

CURRICULUM DEVELOPMENT AND ASSESSMENT: RESULTS

5.1. Characteristics of the Sample

The class that was selected for this study was PHY 112, an introductory, algebra-based physics course that met during the spring semester of 2007 at the University of Maine. Unlike the course from which the interviewees were drawn, PHY 112 is an introductory physics course in which instruction is informed by physics education research, and one in which tutorial instruction is used extensively. It was therefore a natural fit for this curriculum reform effort. The 76 students enrolled in this course had studied simple harmonic motion at the end of the previous semester in PHY 111. Wave motion and sound are included in the PHY 112 curriculum, and lectures on this material had been given prior to the administration of the pretest.

5.2. Pretest Results

The pretest was administered over the course of two days. Forty-six students answered the first four questions. Fifty-eight students answered the last two questions.

5.2.1.   The Radio Speaker Question (Question 1)

The first pretest question involved a radio speaker. Table 5.1 includes a statement of the question along with both the number and percentage of students that selected each response.

Choice A was intended to elicit the stationary particle mental model in which sound is considered to be an entity that passes through the medium without disturbing the medium. Choice B represented the community consensus mental model. Choice C was intended to elicit the flowing air mental model in which sound is considered to push the particles of the medium away from the speaker. Choice D was intended to elicit the hybrid transverse/longitudinal mental model in which sound causes the particles of the medium to oscillate perpendicular to the direction of propagation.

A speaker in a radio converts electrical signals to sound. This is accomplished when the coil in the speaker interacts with the magnet in the speaker	N	(%)
a. Producing electromagnetic radiation which moves away from the speaker.	1	2.2%
b. Causing the speaker cone to move back and forth creating regions of high pressure and regions of low pressure that move away from the speaker.	25	54%
c. Causing the speaker cone to move back and forth pushing air molecules away from the speaker.	8	17%
d. Causing the speaker cone to move back and forth pushing air molecules up and down in front of the speaker.	7	15%
e. I don't really know how a speaker works.	5	11%

Table 5.1. Results from the radio speaker question (Question 1).

Twenty-five students (54%) answered this question correctly. While this was a significantly better performance than that of the interview subjects, it clearly left room for improvement. The higher percentage may have been due to the multiple-choice nature of the question, which perhaps conveyed the intent of the question better than the open-response format in which the question was posed to the interview subjects. Many of the interviewees attempted to describe the internal mechanism of the speaker, rather than just explain how the speaker interacts with the air.

Only one student (2.2%) selected choice A. This might indicate that the stationary particle model is not widely held in this sample. Alternatively, this could be interpreted as evidence that this model exists in this population, but that it is not strongly held in situations where other options are suggested. A greater number of students selected the other two models. Eight students (17%) selected choice C, the flowing air model, and seven students (15%) selected choice D, the hybrid model. The remaining five students (11%) selected choice E indicating that they did not understand how a speaker worked. These results show that a sizable portion of this class relies on mental models that do not match the community consensus model. Further evidence of this is provided by the answers to the second question.

5.2.2. The Sound Wave Propagation Question (Question 2)

If you could see the air molecules in the path between a radio speaker and your ear, you would see	N	(%)
a. The air molecules remaining stationary as the sound moves past them.	4	8.7%
b. The air molecules moving back and forth parallel to the direction in which the sound moves.	22	48%
c. The air molecules moving away from the speaker and toward your ear.	2	4.3%
d. The air molecules moving up and down perpendicular to the direction in which the sound moves.	15	35%
e. I don’t really know what the air molecules would do.	3	6.6%

Table 5.2. Results from the sound wave propagation question (Question 2).

A slightly smaller percentage of the students in this class employed the community consensus mental model in answering this question. Twenty-two students (47.8%) answered Question 2 using this model.

The distribution of answers for this question was quite different from the distribution for Question 1. As with Question 1, choice A was selected to elicit the stationary particle model, choice B was intended to elicit the community consensus model, choice C was selected to elicit the flowing air model, and choice D was intended to elicit the hybrid transverse/longitudinal model.

Four students (8.7%) selected choice A and two students (4.3%) selected choice C. The largest segment of the population, with the exception of those that chose the community consensus model, selected choice D. Fifteen students (33%) selected this option. The remaining three students (6.6%) selected choice E indicating that they did not know what the particles of the medium would do.

A comparison between these two questions is shown in the pivot chart in Figure 5.1. A pivot chart displays the relationship between two sets of data. In this case, student's answers to Questions 1 and 2 on the pretest are compared. The single bar for each response for Question 2 is replaced by several bars. For response B on Question 2, for example, the first bar has a height proportional to the number of students who chose response A for Question 1 and response B for Question 2. The second bar, the one of most interest in this case, has a height that is proportional to the number of students who selected response B for both Questions 1 and 2. The third bar has a height proportional to the number of students that chose response C for Question 1 and response B for Question 2. The fourth bar has a height proportional the number of students who selected response D for Question 1 and response B for Question 2. The fifth bar has a height proportional the number of students who selected response E for Question 1 and response B for Question 2. Had students been absolutely consistent in answering these two questions, there would have been only one bar in this group and it would have had the maximum possible height. At the same time, a number of students selected response B for Question

1 and some other response for Question 2. These students are represented by the bars in the response A, C, D, and E sections of the graph that have a pattern of diagonal lines.

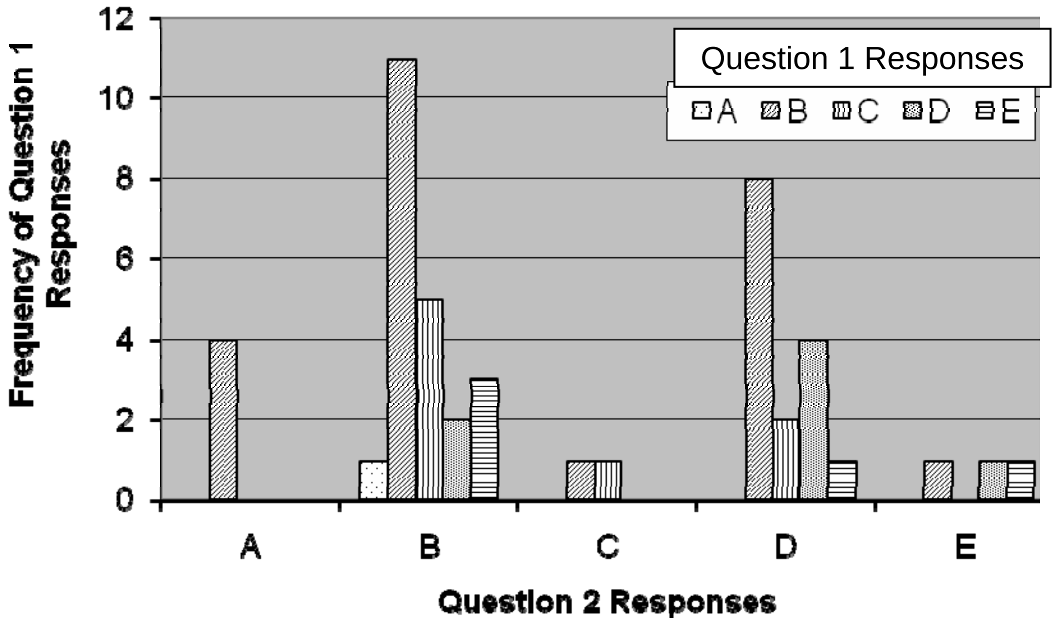

Figure 5.1. Comparison between students' answers for pretest questions 1 and 2.

As can be seen from this chart, even though approximately the same number of students selected choice B, the community consensus model, only 11 students selected this choice for both Question 1 and Question 2. Eight students selected choice B for Question 1 but selected choice D, the hybrid model, for Question 2. Four students selected choice B for Question 1 but selected choice A, the stationary particle model, as the answer for Question 2. At the same time five students who had selected choice C, the flowing air model, for Question 1; selected choice B for Question 2. In addition, three students who had selected option E, two students who had selected option D, and one student who had selected option A as the answer for Question 1; chose option B for Question 2. Clearly a large number of students employed different mental models when answering these two questions. This is consistent with the findings of Hammer (1996) and others who have found that students employ different mental models in different contexts or when answering questions that are stated differently, but is at odds with Palmer (1997), Hrepic et al. (2003) and others.

For the purpose of this study, the important piece of information to note is that, even though approximately half of the students answered each of these questions correctly, only about one quarter of this group consistently employed the community consensus mental model for sound propagation.

5.2.3. The Pressure Question (Question 3)

Question 3 examined students' ability to interpret areas in the diagram where dots were closely spaced as areas where the air pressure was higher than normal atmospheric pressure.

Students were presented with the representation of a sound wave shown in Figure 5.2 and asked to identify regions in which the pressure was higher than normal atmospheric pressure.

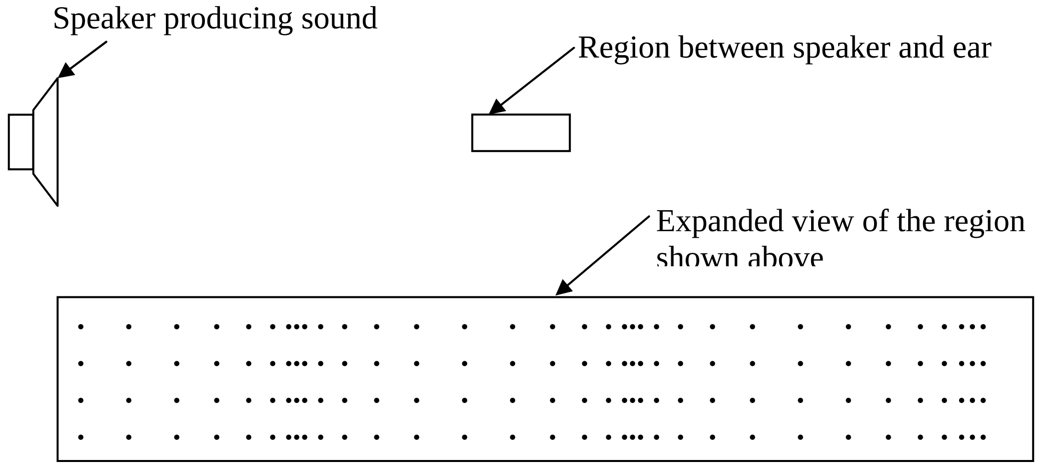

Figure 5.2. Diagram for pretest question 3.

Figure 5.2 shows the distribution of student responses for this question. Response A is correct.

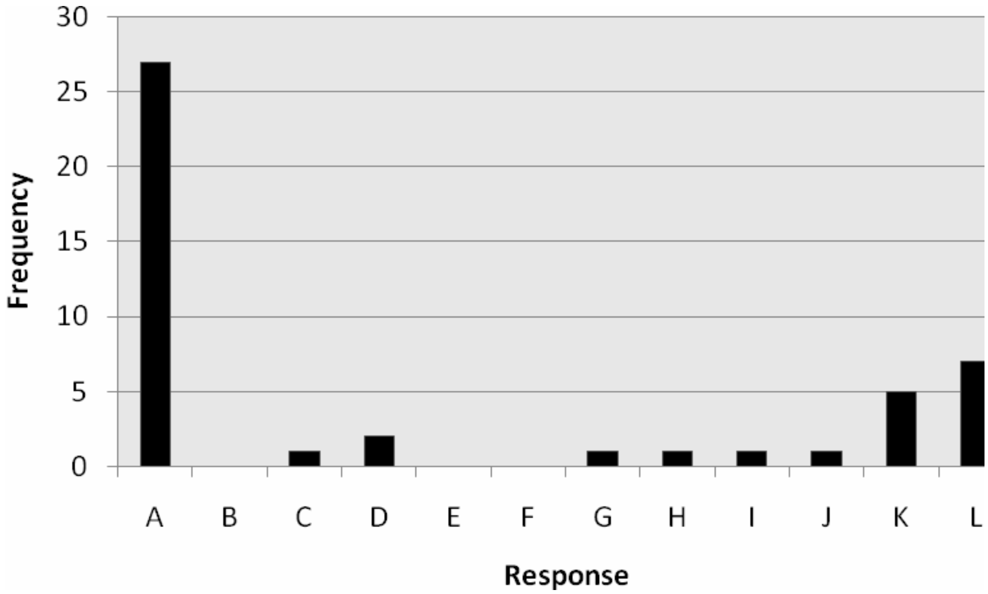

Figure 5.3. Distribution of student responses for question 3. Response is A is correct.

Twenty-seven students (59%) were able to answer this question correctly. One student (2.2%) selected the horizontal rows of dots at the top and at the bottom of the diagram. Two students (4.3%) selected the areas where the dots were widely spaced. One student (2.2%) selected the regions between the closely spaced dots and the widely spaced dots. One student (2.2%) selected the areas that had closely spaced dots as well as areas that contained widely spaced dots. One student (2.2%) indicated that there were no places where the pressure was higher than normal atmospheric pressure. One student (2.2%) did not think that there was sufficient information to answer the question. Six students (13%) indicated that they could not answer the question because they did not understand the diagram. Six students (13%) answered that they did not know how to determine where the pressure was higher than normal atmospheric pressure.

It might be anticipated that students who employed the community consensus model in answering Question 2 would also be among those who answered Question 3 correctly. This is not the case. Only 13 of the 27 students that answered Question 3 correctly also answered Question 2 correctly, while 14 students who utilized other mental models in answering Question 2 were able to select the correct answer for Question 3. The pivot chart shown in Figure 5.4 illustrates these results.

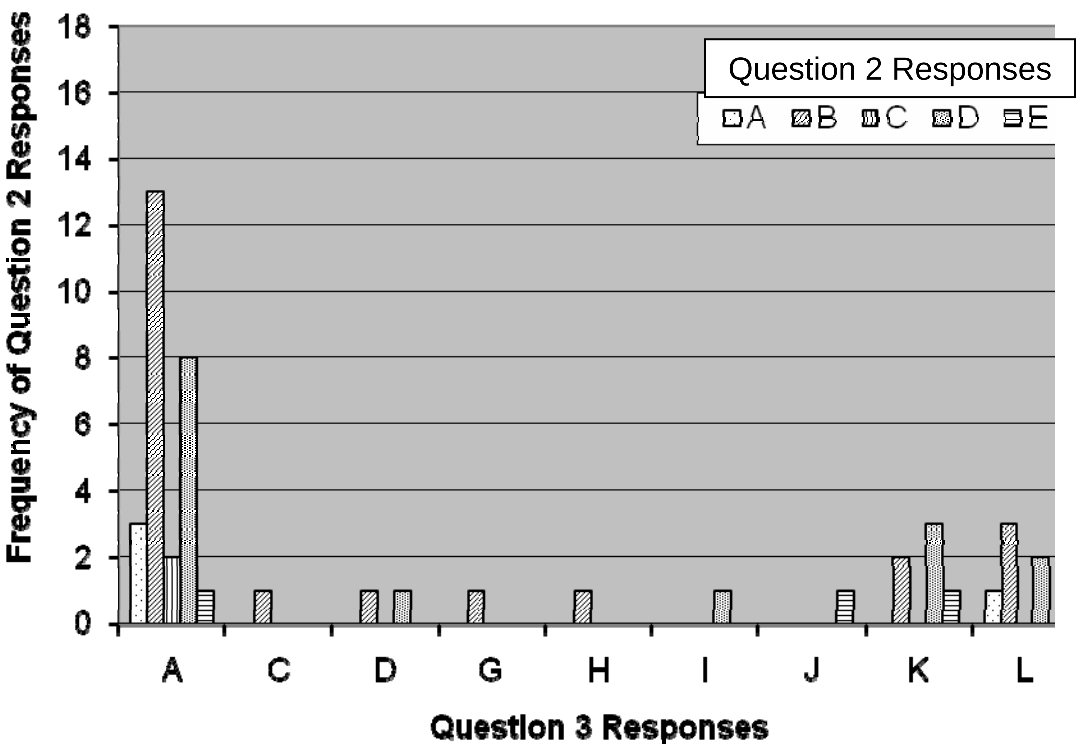

Figure 5.4. Comparison between student answers for questions 2 and 3.

The correspondence between Question 1 and Question 3 was somewhat closer. Seventeen of the 25 students that utilized the community consensus model in answering

Question 1 also answered Question 3 correctly. The distribution of responses for the comparison between question 1 and question 3 is shown in Figure 5.5.

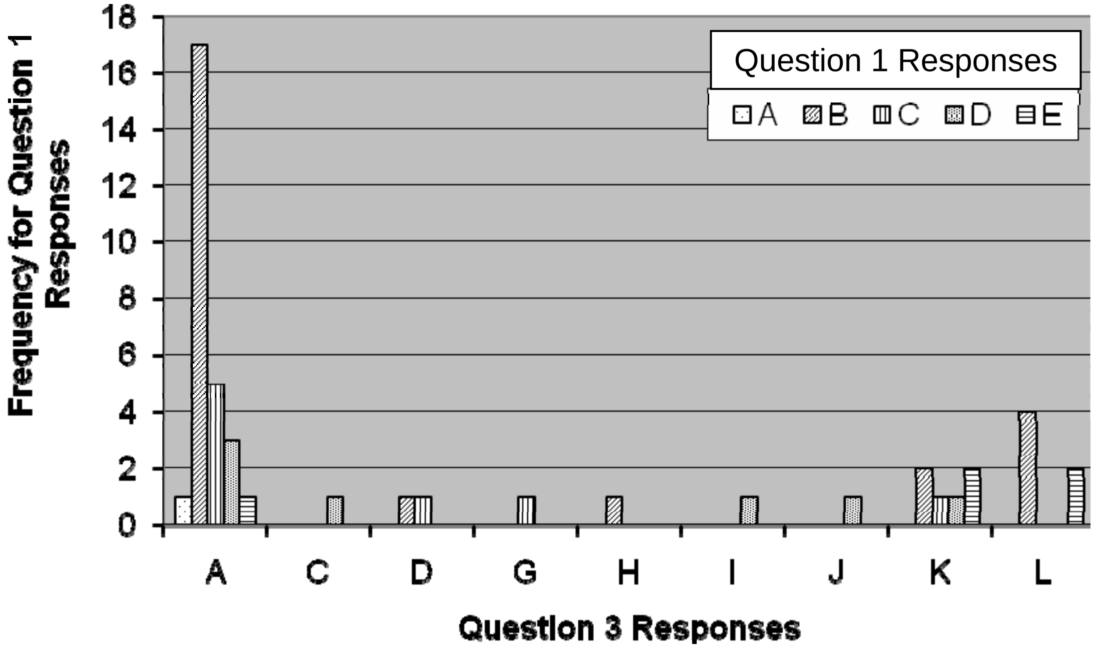

Figure 5.5. Comparison between student answers for questions 1 and 3.

5.2.4. The Particle Motion Questions (Questions 4, 5, & 6)

Questions 4, 5, and 6 examined students' ability to make predictions about the motion of air molecules during sound wave propagation. Students were presented with the diagram of a sound wave shown in Figure 5.2 and asked to identify regions where the particle speed was greatest; and places where the particles were farthest from, and closest to their equilibrium positions.

Very few students answered these questions correctly. One student (2.2%) correctly identified both the regions where the particles were closely spaced and regions where the particles were widely spaced (choice H) as being the places where the particles were moving the fastest. Nine students (20%) identified areas where the particles were closely spaced (choice A) and thirteen students (28%) identified areas where the particles were widely spaced (choice D) as being the locations of maximum speed. Figure 5.6 shows the distribution of responses for question 4. Response H is the correct answer.

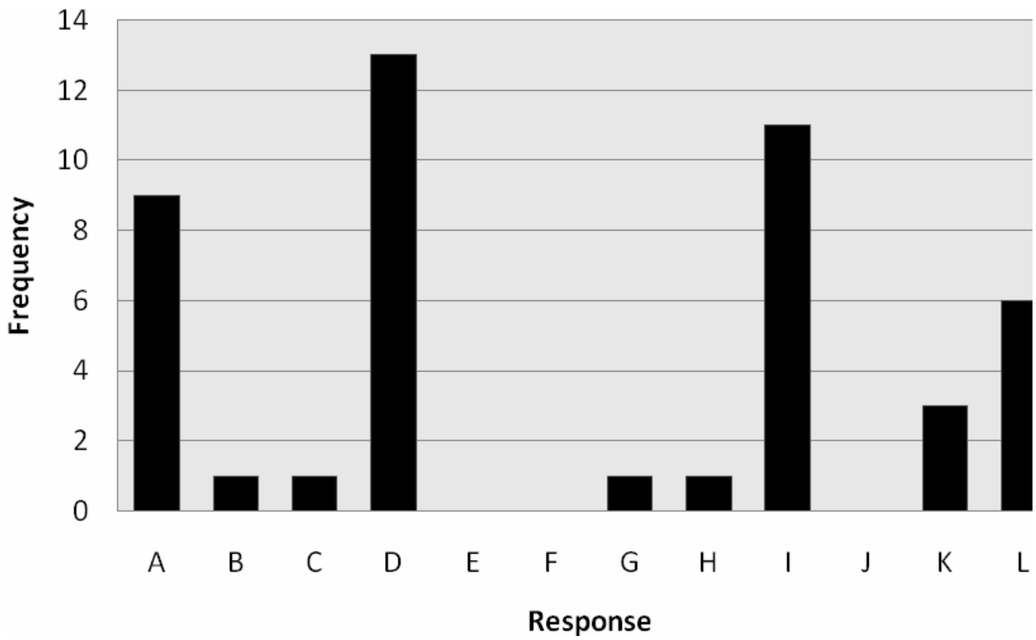

Figure 5.6. Distribution of student responses for question 4. Response H is correct.

No student answered both questions about displacements from equilibrium positions correctly. The most common combination of responses was the choice of response A for Question 5 and response D for Question 6. This corresponds to choosing places where the particles are closely spaced as the places where the particles have a maximum displacement from their equilibrium position and places were the particles are widely spaced as the places where the particles have a minimum displacement from their equilibrium positions. There were four students (6.9%) who selected choice G, the correct response for Question 5; and three students (5.2%) who selected choice H, the correct response for Question 6. Figure 5.7 provides a comparison between the responses for Question 5 and Question 6. Response G is correct for Question 5 and Response H is correct for Question 6.

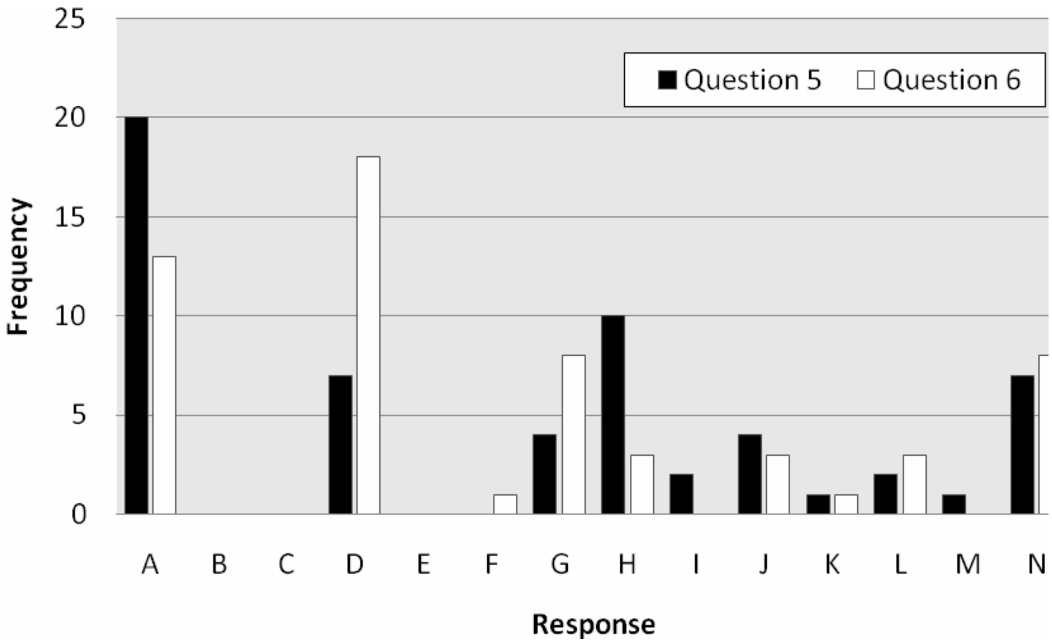

Figure 5.7. Comparison between student answers for questions 5 and 6. Response G is correct for question 5 and response H is correct for question 6.

Some generalizations can be drawn from the pretest results.

- Many students employed the community consensus model when answering the pretest questions about sound wave propagation, however, they were not consistent in applying it either because the model was not strongly held or because the use of the model was context dependent.
- A large number of students were able to correctly identify the regions in the diagram where the particles were close together as sound wave compression regions. Most students who were not able to do this had difficulty interpreting the diagram. They either did not understand the

information presented in the diagram, or they were unable to use that information to determine where the compressions were located. This might have been caused by a lack of a clear understanding of pressure and how it relates to the distribution of the particles of the medium.

- The most frequently selected answer for the maximum particle speed question was the rarefaction regions of the sound wave. An almost equal number of students predicted that all particles have the same speed. This second selection fits with the entity model for sound wave propagation were sound passes through the medium but is separate and distinct from the medium. It either does not affect the particles of the medium, or pushes the particles of the medium aside. As with the previous question, a substantial number of students were unable to interpret the diagram.
- In identifying the points of maximum and minimum displacement, the most common answer was that the particles have the maximum displacement in the regions of compression and minimum displacement in the regions of rarefaction. A logical interpretation of this combination of responses is that these students pictured the particles of the medium as moving from the regions of rarefaction to the regions of compression leaving those that were in the regions of rarefactions near their equilibrium positions and those that were in the regions of compression far from their equilibrium positions. These students might have been reasoning from past experiences in which, in order to increase the amount of a substance at one location, it is necessary to remove it from another location. As with

the previous questions, a substantial number of students were unable to interpret the diagram.

5.3. Pretest – Post-Test Comparisons

Unfortunately, some students who took the pretest did not take the post-test and some students who took the post-test did not take the pretest. To facilitate a comparison between the pretest and post-test data in order to evaluate the effectiveness of the tutorial, only the responses from the students who answered corresponding questions on both the pretest and the post-test were included in the following analysis.

5.3.1. The Sound Propagation Question

Thirty-four students answered the question on propagation of sound on both the pretest and the post-test. While only 16 students (47%) used the community consensus model when answering this question on the pretest, 29 students (85%) selected this option on the post-test. Three students regressed. They selected the community consensus model on the pretest and one of the other models on the post-test. Two students (5.9%) selected the hybrid model and one student (2.9%) selected the flowing air model. However, 16 students (47%) who had selected one of the other models on the pretest chose the community consensus model on the post-test. A comparison of the pretest and post-test responses on the sound propagation question is provided by the pivot chart in Figure 5.8.

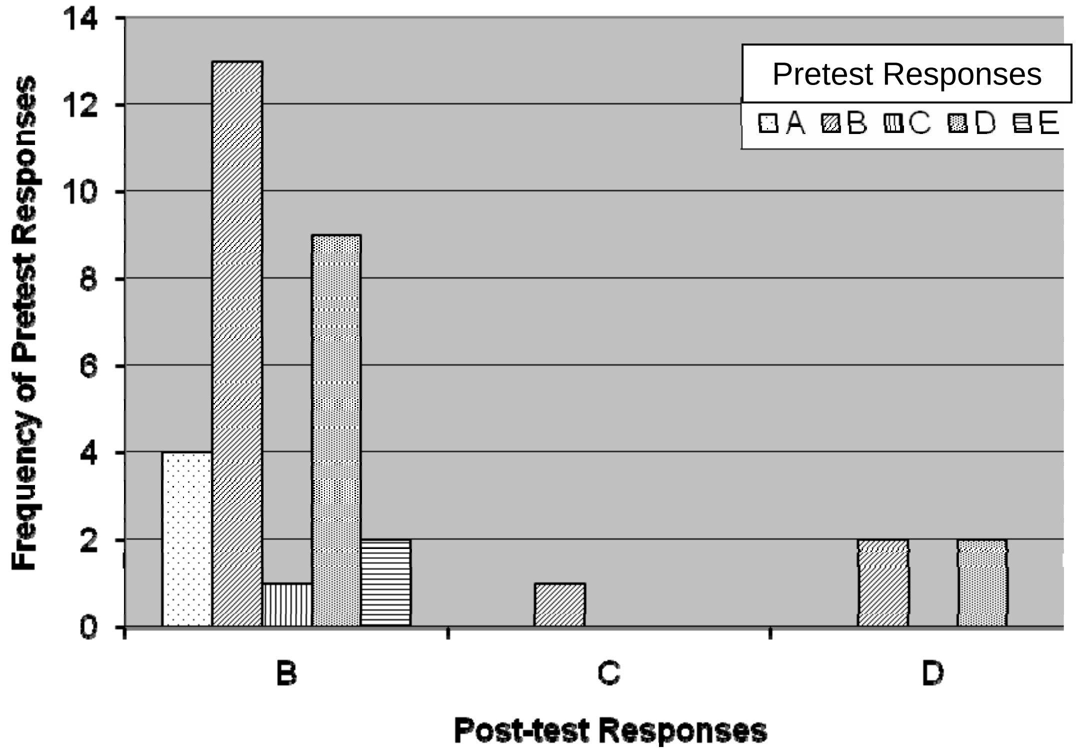

Figure 5.8. Comparison between students' pretest and post-test answers for the sound propagation question.

5.3.2. The Pressure Question

The questions pertaining to relative air pressure and particle motion used different representations for the choices on the pretest and the post-test. On the pretest students were asked to select one option from the series of diagrams shown in Figure 5.9.

On the post-test, students were asked to select regions on a diagram representing a sound wave. They were asked to select all areas that met the criterion specified in the question. These questions on the post-test were probably more difficult versions of the questions on the pretest since students were asked to identify specific regions on the diagram rather than just choose from among several predefined options. Figure 5.10 is a reproduction of this diagram.

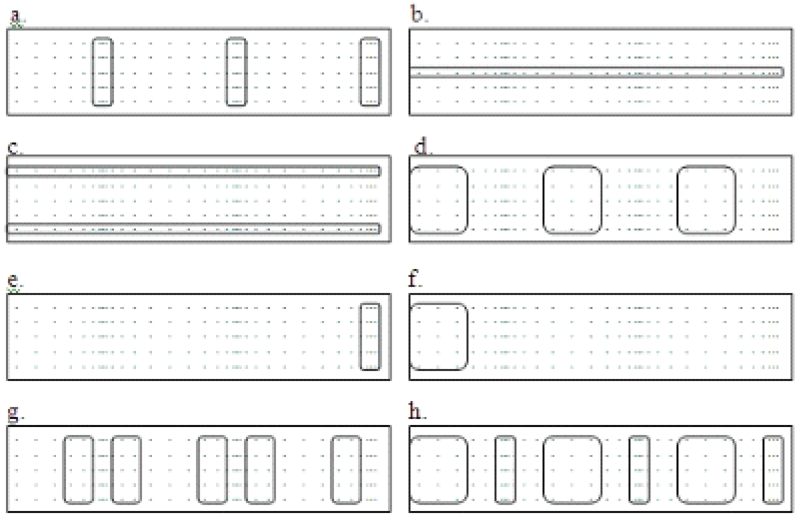

Figure 5.9. Options for the pressure and particle motion questions on the pretest.

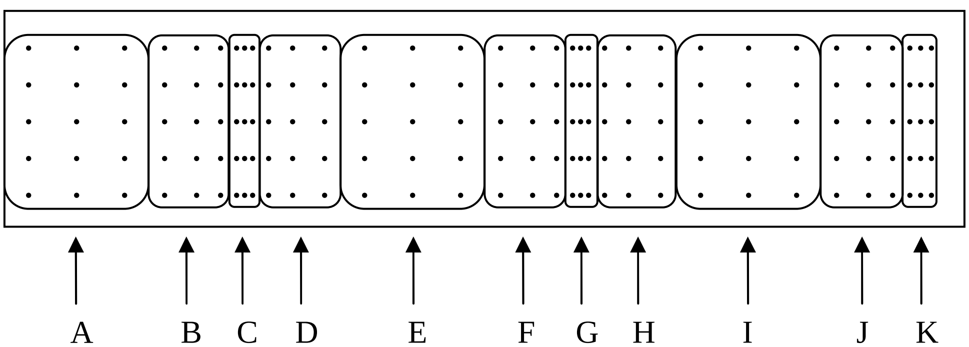

Figure 5.10. Options for the pressure and particle motion question on the post-test.

To the extent possible, the answers on the pretest and the corresponding answers on the post-test were assigned the same letter. For example, a student that selected regions C, G, and K on the post-test was assigned the code letter A, the same letter that these regions were assigned on the pretest. A response on the post-test that did not correspond to any option on the pretest was coded as O. That allowed the responses for a question on the post-test to be compared to the responses for the corresponding question on the pretest by comparing the letters that identified the regions that were selected. Two choices on the pretest, B and C, were not included as options on the post-test. These were not expected to have a high probability of being selected following instruction. Table 5.3 is a compilation of the possible pretest answers and codes for the corresponding post-test answers.

	Pretest Answers	**Post-test Codes**	**Post-test Answers**
Compressions	A	A	CGK
Center Row of Particles	B		Not included as an option.
Top and Bottom Rows of Particles	C		Not included as an option.
Rarefactions	D	D	AEI
Particles Farthest from Speaker	E	E	K
Particles Closest to Speaker	F	F	A
Locations of Equilibrium Pressure	G	G	BDFHJ
Compressions and Rarefactions	H	H	ACEGIK
Other Combinations		O	ACG, BD, CBFJ, CFI, CGJ, and others.

Table 5.3. Pretest answers and codes for corresponding post-test answers.

On the pretest, students were asked to identify areas of higher than normal pressure. On the post-test students were asked to identify areas of lower than normal pressure. Consequently, option A represented a correct answer on the pretest and option D represented a correct answer on the post-test.

Thirty-six students answered this question on both the pretest and the post-test. Twenty-four students (66.7%) answered this question correctly on the pretest. Thirty students (83.3%) answered the question correctly on the post-test. Only one student (2.8%) answered the question on the pretest correctly and wrong on the post-test. This person selected regions where the dots were more closely spaced rather than where they were more widely spaced, which could have been the result of misreading the question.

Seven students (19.4%) who were not able to answer the question correctly on the pretest, were able to identify regions where the air pressure was lower than normal atmospheric pressure on the post-test. A comparison between the pretest and the post-test responses for this question is illustrated in the pivot chart in Figure 5.11.

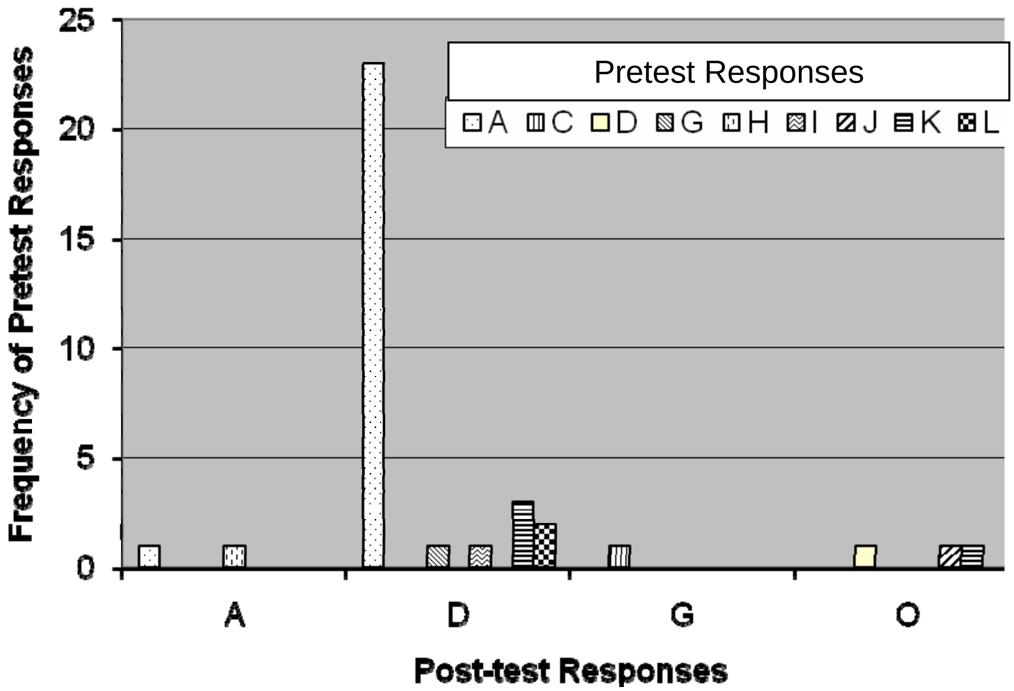

Figure 5.11. Comparison between students' pretest and post-test answers for the pressure question.

Students were asked to explain their reasoning on the post-test questions. This provided some additional information. Most did not write anything. Those that did, for the most part, answered the question correctly and thought that the pressure would be lowest where the particles were most widely spaced. One student who selected the correct areas, however, wrote, "The necles [sic] are spaced out so therefore, not as much constructive interference as in say c, g, and k." One student that selected the regions between the closely spaced dots and the widely spaced dots wrote, "Troughts, [sic] that is where there is low pressure." Evidently she mistakenly thought that the regions she identified corresponded to troughs on a longitudinal wave.

5.3.3. The Particle Motion Questions

Improvement in understanding of the motion of the particles of the medium during sound wave propagation was much lower than the improvement in other areas. Students were asked where the particles of the medium were moving the slowest, and where the magnitude of the displacement from the equilibrium position was a maximum and where it was a minimum.

5.3.3.1. The Particle Velocity Question. Question 4 on the pretest asked students to predict the points in the diagram where the particles of the medium would be moving the fastest. Students should have selected the places where the particles were closest together and where they were farthest apart. Thirty-five students answered this question. Only one student (2.9%) answered this question correctly on the pretest. Seven students (20.0%) were able to correctly identify the point midway between the closely spaced dots and the widely spaced dots as the place where the particles were moving the slowest on the post-test. While this is evidence that there was some increase in understanding as a result of using the tutorial, the post-test results were still lower than had been expected. Figure 5.12 shows the distributions of scores for the particle speed questions on the pretest (white bars) and post-test (black bars). Response H is the correct answer for the pretest. Response G is the correct answer for the post-test.

Three students who answered this question correctly on the post-test also made an attempt to explain their reasoning. In at least two of these explanations there is evidence that they used the simple harmonic motion mental model for the motion of the particles of the medium presented in the tutorial in arriving at their answers. One wrote, "Because they have max v at the equilibrium position and min when far from this which is when the particles aren't scrunched or spread out." A second student wrote, "They are at max displacement so v=0." The third student was much more cryptic. He wrote, "v=Δd/Δt Δt is less."

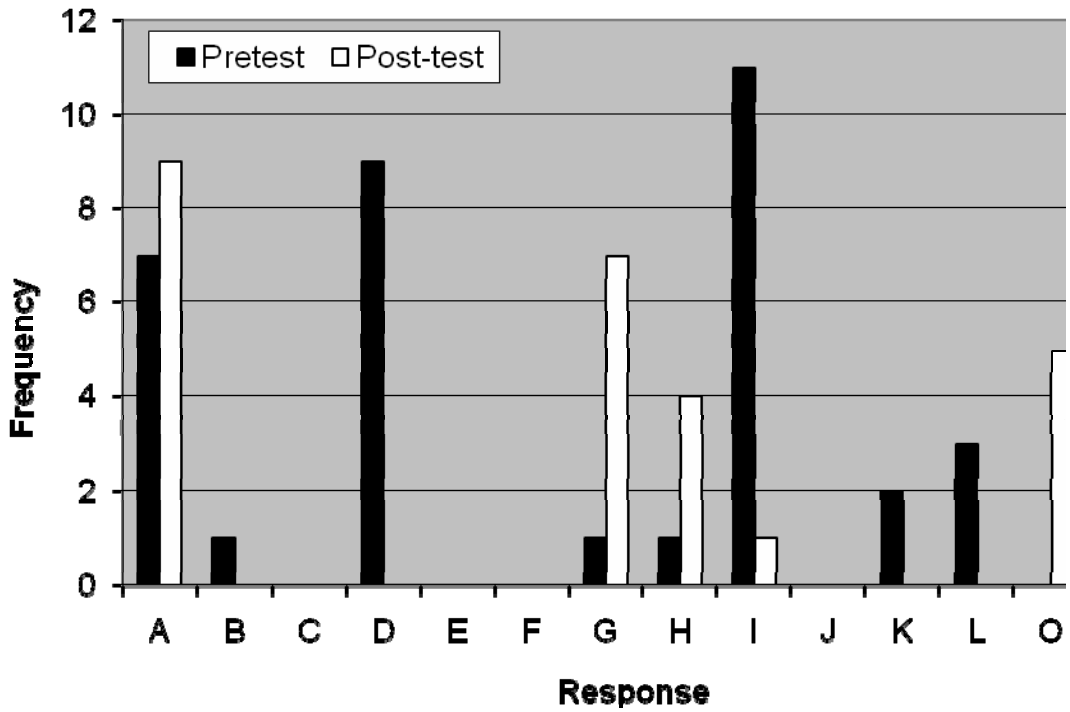

Figure 5.12. Distribution of student responses for the particle velocity question on the pretest and post-test. Response H is correct on the pretest and response G is correct on the post-test.

Several students who answered this question incorrectly provided an explanation for their reasoning. Three students selected the regions in the diagram where the dots were close together. They seemed to think that the particles would move slower where the pressure was highest. One wrote, "The molecules are compressed and move slower." Another wrote, "low velocity = high pressure." Two students selected regions where the dots were widely spaced. One wrote, “More space between molecules, so takes longer to travel same distance = smaller velocity.” The other wrote “Where no wave passes through.” Three students selected both the regions containing closely spaced dots and those containing widely spaced dots. Their explanation of their reasoning suggests that they might have been employing the simple harmonic motion mental model, but reversed the positions of maximum and minimum velocity and displacement. One wrote, “Because it’s slowed and reversing direction.” Another wrote, “Max velocity in between extremes.” The third wrote, “At these points the velocity is or is near zero.” One student selected all of the points and wrote, “If they are all moving together . . . don’t they have the same velocity?” Clearly this student was not using the simple harmonic motion mental model presented in the tutorial.

5.3.3.2. The Particle Displacement Questions. The results for the particle displacement questions were similarly disappointing. Forty students answered the particle displacement questions on both the pretest and the post-test. On the pretest, three students (7.5%) correctly identified the regions midway between places where the dots were most closely spaced and places where the dots were most widely spaced as the regions where the particles of the medium have a maximum displacement from their equilibrium positions. Two students correctly identified both the places where the dots were most closely spaced and the regions where the dots were most widely spaced as the regions where the particles of the medium have the minimum displacement from their equilibrium positions. There was no overlap in these two groups, indicating that a correct answer on one of the questions was probably not the result of a thorough understanding of the motion of the particles of the medium during sound propagation.

On the post-test, six students (15%) correctly identified the points of maximum displacement and five students (13%) correctly identified the points of minimum displacement. The results were somewhat more dramatic when the four pretest and post-test questions were considered as a group. No one answered both question 5 and 6 correctly on the pretest, while four students (10%) answered both questions 4 and 5 correctly on the post-test.

Seven students explained their reasoning in answering either one or both of the particle displacement questions. Three of these students answered both questions correctly, and the descriptions of their reasoning indicated that they used the simple harmonic motion mental model presented in the tutorial to arrive at their answers. One, in fact wrote, “I remember from the tutorial.” A second student wrote, “An air molecule is in equilibrium when it is compressed or rarefacted.” The third student wrote, “Equilibrium is where they are most spread out or the most scrunched up. Other places are far from that.” Two of these students answered the particle velocity question correctly as well as the particle displacement questions. The third student selected the regions of compression, but not the regions of rarefaction in answering the particle velocity question.

The four students who answered this question incorrectly and provided an explanation of their reasoning reversed the correct answers. They chose the points of maximum compression and maximum rarefaction as the points of maximum displacement and the points in between as the points of minimum displacement. None of these students provided explanations that contained much information. For the maximum displacement question one wrote, “They look like they’re about the same displacement from the normal." For the minimum displacement question he wrote, "Can't go wrong with the middle of the road when it comes to equilibrium." A second wrote, "Move farthest from the starting point," and "Normal" for these questions respectively. The third wrote "These are the farthest from the norm, which is ¼ λ past the norm."

5.3.4. The Time-shifted Sound Wave Question

The last question on the post-test presented students with a diagram representing a sound wave and asked them to draw what the sound wave would look like a short time later, one quarter of the period of the sound wave or less. There was no corresponding question on the pretest. Of the twenty-nine students who answered this question, thirteen students (45%) drew diagrams that were considered to be correct representations of the time-shifted sound wave. Five students (17%) drew waves that were shifted to the left rather than to the right, even though the source (speaker) was at the left end of the figure. Two students (6.9%) drew a sound wave that was shifted one half period rather than one quarter period. One student (3.4%) drew a diagram of a sound wave that was identical to the one in the diagram provided. One student (3.4%) drew a diagram of a transverse wave. One student (3.4%) drew a diagram that was not correct even though the explanation provided by that student was one which should have lead to a correct diagram. Six students (21%) drew diagrams that were impossible to decipher.

5.4. Summary of Pretest and Post-test Results

The results for the pretest questions for students who took both the pretest and the post-test are summarized in Table 5.4. The results for the post-test questions for students who took both the pretest and the post-test are summarized in Table 5.5. The number of students selecting each response for each question is listed in the table. The correct answer for each question is identified with an asterisk.

Response	Radio Speaker	Sound Prop.	Pressure	Particle Velocity	Maximum Displacement	Minimum Displacement
A	0	4	24*	7	15	5
B	20*	16*	0	1	0	0
C	5	1	1	0	0	0
D	6	11	1	9	4	16
E	3	2	0	0	0	0
F			0	0	0	1
G			1	1	3*	5
H			1	1*	6	2*
I			1	11	0	0
J			1	0	4	3
K			4	2	1	1
L			2	3	1	2
M					0	0
N					5	5

Table 5.4. Summary of pretest results for students who took both pretest and post-test.

Response	Sound Prop.	Pressure	Particle Velocity	Maximum Displacement	Minimum Displacement
A	0	2	9	10	4
B	29*	0	0	0	0
C	1	0	0	0	0
D	4	30*	9	6	8
E	0	0	0	0	0
F		0	0	0	0
G		1	7*	6*	18
H		0	4	16	5*
I		0	1	0	0
J		0	0	0	0
K		0	0	0	0
L		0	0	0	0
M		0	0	0	0
N		0	0	0	1
O		3	5	2	4

Table 5.5. Summary of post-test results for students who took both pretest and post-test.

As can be seen from the data in these tables, using the tutorial resulted in an increase in the number of students correctly answering each of the questions. Thirteen additional students (38%) correctly answered the sound propagation question which was question 2 on the pretest and question 1 on the post-test. Six additional students (17%) correctly answered the air pressure question which was question 3 on the pretest and question 2 on the post-test. An additional six students (17%) correctly answered the particle velocity question which was question 4 on the pretest and question 3 on the post-test. While no student correctly answered both questions 5 and 6, the particle displacement questions, on the pretest, four students (10%) answered the corresponding questions correctly on the post-test.

These results indicate that the objective of Part I of the tutorial was met. A significantly greater number of students used the community consensus model for sound wave propagation on the post-test.

The improvement in students' ability to recognize compressions and rarefactions, and the accuracy with which they were able to do so, indicate that this objective of the tutorial was also met. This objective was addressed in Part VI of the tutorial.

Use of the tutorial to acquaint students with the simple harmonic motion model for the motion of the particles of the medium during longitudinal wave propagation, and have them apply this model to sound met with limited success. A number of students did indeed use the simple harmonic motion model when answering the post-test questions; however, that number was small. Most students either did not use the model, or employed it incorrectly when answering the post-test questions. It is not clear if this was a consequence of students failing to assimilate the model, or students failing to correctly apply the model to sound wave propagation. In retrospect, this points to a need for additional questions on the pretest and the post-test. This would make it possible to determine if the model itself, the focus of Part III of the tutorial; the application of the model, addressed in Part IV of the tutorial; or both require revision.

The small number of matched questions on the pretest and post-test, and the relatively small number of students who answered all of these questions on both tests, made a statistical analysis of the data somewhat problematic. A statistical analysis of individual questions was not possible as it would have yielded results below the limit of validity for a t-test. A paired t-test was performed on the five matched questions (sound wave propagation, pressure, particle velocity, and maximum and minimum particle displacement) from the pre- and post-tests. The mean for the pre-test was 1.32 and the mean for the post-test was 2.14. The difference between the means was 0.82. Although the difference in the means was small, by conventional criteria it is considered to be statistically significant. The P value generated by the t-test was equal to 0.0017. A P value of 0.0017 means that, in randomly selected samples, a difference between the means of the two tests larger than .82 would occur only 17 times in 10,000. The t-test, therefore, provided further evidence that the tutorial did improve students' understanding of longitudinal wave propagation. Most of this improvement seems to have resulted from increased numbers of students using the community consensus mental model for sound propagation and developing improved comprehension of pressure variations in sound waves. Much less of the improvement was due to increased understanding of the motion of the particles of the medium during sound propagation.

CHAPTER 6

CONCLUSIONS

This study was motivated by an interest in the following research questions:

- What models of sound wave propagation do students in introductory physics courses at the University of Maine employ prior to implementation of a research based curriculum reform effort, and are these models similar to the models used by students in other populations?
- Is it possible to develop instructional materials that significantly increase the number of students utilizing the community consensus model for the propagation of longitudinal waves in general, and sound in particular?
- To what extent can students assimilate a mental model that will enable them to accurately describe, in detail, the motion of the individual particles of the medium as a longitudinal wave is propagated through it? Accurately describing in detail is defined as being able to identify the particles in the medium that have a maximum and a minimum magnitude for their acceleration, velocity, and displacement from the equilibrium position as a longitudinal wave is being propagated through the medium.

The following sections will examine the degree to which these questions have been answered and provide directions for future research.

6.1. Student Mental Models of Longitudinal Wave Propagation

Evidence was found for three mental models for the propagation of sound in addition to the community consensus model. These models correspond to some of the mental models described in previous research on sound wave propagation by Linder (1992), Hrepic et al. (2002), and Wittmann et al. (2003). The fist mental model, the stationary particle model, is a “sound as entity” or “sound as object” model in which sound is perceived as an entity that passes through the medium without disturbing the particles of the medium. In the population surveyed in this study, a relatively small number of students used this mental model when answering questions about sound propagation. A second entity model was also found. In this model, the flowing air model, sound is pictured as an entity that is separate and distinct from the particles of the medium, which it pushes aside as it propagates. As with the first entity model, only a small number of students in this study used this model when answering questions about sound wave propagation. The third model was a hybrid transverse/longitudinal model in which students pictured the particles of the medium as moving, but oscillating perpendicular to the direction of propagation, rather than parallel to it. This model was used by the largest number of students in this study, other than those that used the community consensus model.

Even though the community consensus model was used by the largest number of students, the use of this model was not consistent. Approximately half or the students who answered the first question on the pretest using the community consensus model used a different model on the second question, and approximately half of the students who did not use the community consensus model on the first question used it when answering the second question. This is consistent with previous research by Hammer (1996) and others which showed that students sometimes use different mental models in different contexts, but conflicts with the findings of Palmer (1997), Hrepic et al. (2003) and others.

Interestingly, the interview subjects were much more evenly distributed in the mental models that they employed. Three of the interview subjects appeared to use the community consensus model, two used the flowing air sound model, two used the stationary particle model, and two used the hybrid transverse/longitudinal model.

It is possible to say, therefore, that the mental models that were found in this sample population were similar to those that have been most frequently reported previously in the literature. The distribution of the models that were employed by the interview group from the PHY 122 class was different from the distribution of models used by the pretest/post-test group from the PHY 112 class. The distribution of each group was somewhat different than those that have been previously reported. This was not unexpected since the populations were different. Examining differences among diverse populations is becoming a more prominent research area lately.

6.2. Enhancing Student Understanding of Longitudinal Wave Propagation Using a Tutorial

The first part of the tutorial targeted the mental models that students use in answering questions about propagation of sound. The results from the pretest and post-test provide evidence that the tutorial was at least partially successful in causing students to consider various mental models for the propagation of sound and recognize that the community consensus model is the model that best accounts for observable phenomena related to sound propagation.

When asked about the behavior of the particles of the medium during the propagation of sound, students were much more likely to select the community consensus model on the post-test, taken after completing the tutorial, than on the pretest. Less than half (47%) of the students who answered the question on the pretest chose the community consensus model. When answering the corresponding question on the post-test, 85% selected the community consensus model. A post-test prevalence of 85% is in line with scores by students using instructional methodologies that have been considered successful.

These results are somewhat better than those reported by Wittmann et al. (2003). The tutorial they developed served as a model for the construction of the first part of the tutorial used in this study. They found that 26% of students used the community consensus model before completing their tutorial and 45% used it after completing the tutorial.

It is, therefore, possible to develop an instructional methodology that results in a substantial increase in the number of students who employ the community consensus model for the propagation of longitudinal waves.

6.3. Student Perceptions about the Microscopic Behavior of the Particles in the Medium During Longitudinal Wave Propagation

The tutorial was found to be much less effective in changing students' mental models related to the detailed microscopic behavior of the particles of the medium during the propagation of sound.

There was some improvement in the results for the question concerning pressure differences in a sound wave. A significant number of students (69%) were able to identify regions of high particle density as being areas where the air pressure was higher than normal atmospheric pressure on the pretest. An even greater number of students, 85%, were able to identify regions of low particle density as being areas where the air pressure was lower than normal atmospheric pressure on the post-test.

The number of correct answers to the questions pertaining to the speed and displacement of the particles of the medium showed only a small improvement from pretest to post-test. Three percent of the students correctly identified the places where the particles have the maximum speed on the pretest, while 20% were able to identify the places where the particles have the minimum speed on the post-test. While no students were able to identify both the places where the displacement of the particles would be a maximum and where it would be a minimum on the pretest, 10% were able to do this on the post-test. Evidence from the explanations that these students gave for their answers strongly indicates that at least some were able to do this because of the tutorial.

It is possible therefore, for a number of students in an algebra-based introductory physics course to assimilate a mental model that allows them to describe, in detail, the behavior of the particles of the medium during longitudinal wave propagation; however, that number is small.

6.4. Suggestions for Further Research

This study has suggested a number of areas where future research is possible. Several of these are described below.

6.4.1. Refine the Tutorial to Improve its Effectiveness

Curriculum development is an iterative process. This work represents an initial attempt which can serve as a basis for future modifications. The improvement in student understanding of the displacements and velocities of particles during sound wave propagation was disappointing, and suggests the need for refinements to the tutorial. The lack of improvement could have been the result of students' failure to assimilate the simple harmonic motion model for longitudinal waves, their failure to apply the model to sound, or both. Investigating the cause of the problem and modifying the tutorial accordingly could address the shortcomings of the tutorial as it is currently written and result in greater student understanding of sound wave propagation.

6.4.2. Examine the Correlation between the use of the Tutorial and Improvement on the Post-test

No attempt was made in this study to evaluate the extent to which individual students engaged in the tutorial. It is possible that a student may have been absent during the tutorial classes, but present for both the pretest and post-test. It is also possible that a student may have been present during the tutorial classes, but not focused on the tutorial. The tutorial classes took place near the time of an exam and students were aware of the fact that there would be no questions on the exam pertaining to the tutorial material.

It would be instructive to collect data on how effectively students were engaged with the tutorial, either by classroom observation or by collecting the tutorials from students and evaluating them, then correlating this data with the results from the pretest and post-test.

6.4.3. Investigate the Effects of Modifying Instruction in Higher Level Classes

Although some improvement in the post-test questions over the corresponding pretest questions related to the behavior of the particles of the medium as a consequence of the simple harmonic motion model introduced in the tutorial was found, this improvement was small. It would be useful to examine the effectiveness of the tutorial on a class with a deeper understanding of simple harmonic motion such as a calculus-based introductory physics course or an upper-level undergraduate mechanics course.

6.4.4. Explore Student Interpretations of Graphical Representations

During interviews, students were asked to draw and interpret diagrams of longitudinal waves. These diagrams were intended to be pictorial representations of the wave, not graphs, and were described as such. The pretest and the post-test each contained similar diagrams. It is not clear that students interpreted them as snapshots. The prevalence of the hybrid transverse/longitudinal model might be partially explained by students attempting to draw a graph rather than a diagram. This possibility was only recognized late in the interview process. The last three students interviewed were asked to describe what they saw when they were shown a pictorial representation of the sound wave. Most were able to do so reasonably well, but they were also the students who demonstrated the best understanding of sound wave propagation. Since graphical representations of many kinds are used extensively in physics, examining how students interpret diagrams of longitudinal waves could represent a significant research opportunity.

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Appendix A

INTERVIEW PROTOCOL

Interview Protocol

1. Think about a radio speaker that is producing a sound with a constant pitch. How do you think the radio speaker produces the sound that you hear.

2. Describe how you think the sound gets from the speaker to your ear.

3. Imagine that you could see the air molecules in the path between the speaker and your ear. Do you think that the air molecules move? If so, describe the motion of one of the air molecules as the sound from the speaker passes.

4. Imagine that you could take a snapshot of the air molecules in the path between the speaker and your ear. For this particular instant in time, draw what you think this snapshot would look like. You can represent the individual air molecules as dots. Explain why you drew the diagram the way you did.

5. This is a diagram that might have been drawn representing a snapshot of the air molecules as a sound wave passes by. The dots (point to a dot) represent air molecules. What do you see when you look at this diagram?

6. Would you draw what the diagram would look like a short time later.

7. Draw arrows on the diagram that point toward places in the diagram that represent areas where the pressure is higher than normal air pressure, if there are any, and label the arrows H. Explain how you decided where to draw the arrows.

8. Draw arrows on the diagram that point toward places in the diagram that represent areas where the pressure is lower than normal air pressure, if there are any, and label the arrows L. Explain how you decided where to draw the arrows.

9. Draw arrows on the diagram that point toward places in the diagram that represent areas where the molecules are moving the fastest, if there are any, and label the arrows F. Explain how you decided where to draw the arrows.

10. Draw arrows on the diagram that points toward places in the diagram that represent areas where the molecules are moving the slowest (or not at all), if there are any, and label the arrows S. Explain how you decided where to draw the arrows.

11. Draw arrows on the diagram that point toward places in the diagram that represents areas where the molecules have the maximum displacement from their equilibrium position, if there are any, and label the arrows Max. Explain how you decided where to draw the arrows.

12. Draw arrow on the diagram that point toward places in the diagram that represent areas where the molecules have the minimum displacement from their equilibrium position, if there are any, and label the arrows Min. Explain how you decided where to draw the arrows.

13. Make two marks on the diagram that are approximately one wavelength apart. Explain how you decided where to draw the marks.

14. Think about a long slinky that is stretched the length of the corridor outside the room. Imagine that someone is shaking one end of the slinky from side to side at a constant rate and that the slinky is long enough so that waves do not have time to reflect from the other end. Visualize one of the coils of the slinky. Do you think that the coil of the slinky is moving? If so, describe the motion of the coil.

15. Imagine that you could take a snapshot of the slinky. Draw what you think this snapshot would look like. You can represent the slinky as a line, you do not need to draw the individual coils of the slinky. Explain why you drew the diagram the way you did.

16. This is a diagram that might have been drawn representing a snapshot of the slinky as a wave passes by. Draw arrows on the diagram that point toward places in the diagram that represent areas where the coils of the slinky are moving the fastest, if there are any, and label the arrows F. Explain how you decided where to draw the arrows.

17. Would you draw what the diagram would look like a short time later?

18. Draw arrows on the diagram that point toward places in the diagram that represent areas where the coils of the slinky are moving the slowest, if there are any, and label the arrows S. Explain how you decided where to draw the arrows.

19. Draw arrows on the diagram that point toward places in the diagram that represents areas where the coils of the slinky have the maximum displacement from their equilibrium position, if there are any, and label the arrows Max. Explain how you decided where to draw the arrows.

20. Draw arrows on the diagram that point toward places in the diagram that represent areas where the coils of the slinky have the minimum displacement from their equilibrium position, if there are any, and label the arrows Min. Explain how you decided where to draw the arrows.

21. Make two marks on the diagram that are approximately one wavelength apart. Explain how you decided where to draw the marks.

Appendix B

INTERVIEW SUBJECTS' SOUND WAVE DIAGRAMS IDENTIFYING MAXIMUM AND MINIMUM PRESSURE, PARTICLE VELOCIY, AND PARTICLE DISPLACEMENT

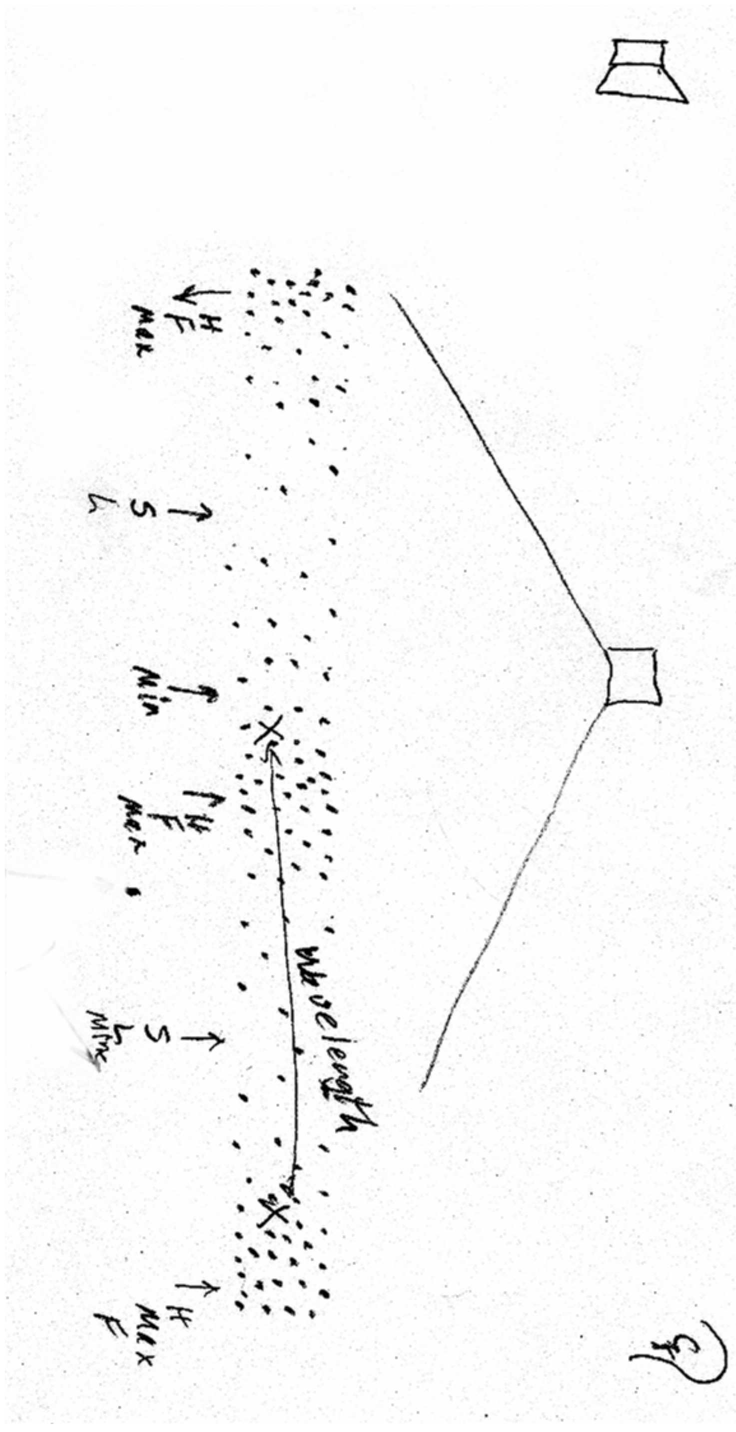


Figure B.1. Rita's Diagram.

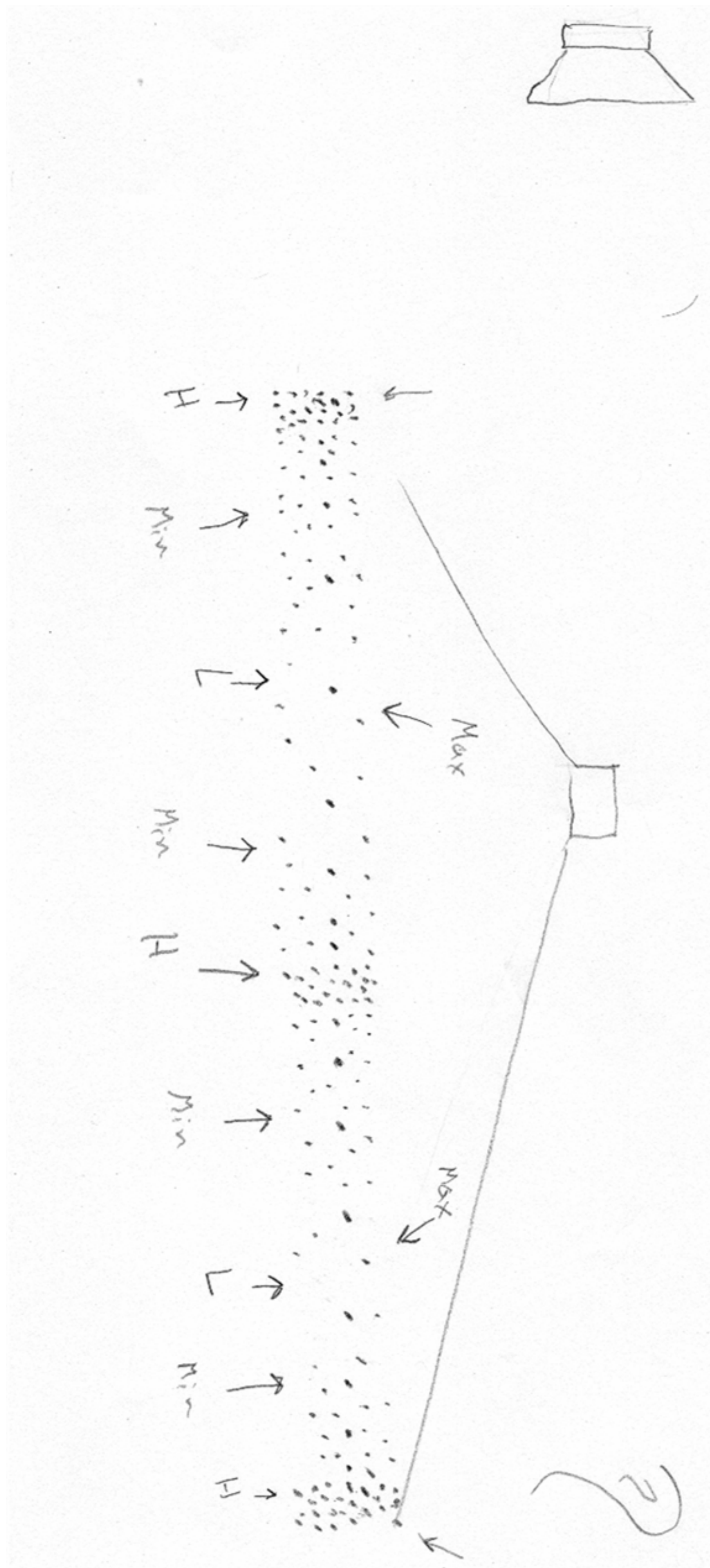


Figure B.2. Ralph’s Diagram.

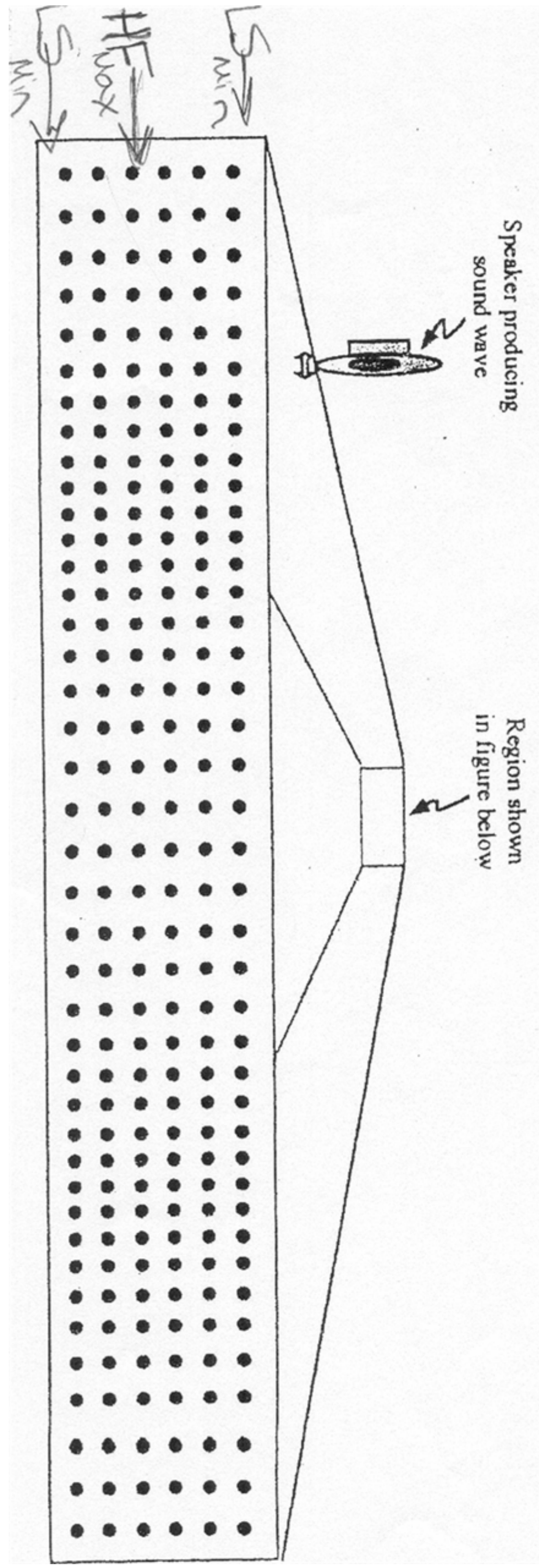


Figure B.3. Steve's Diagram.

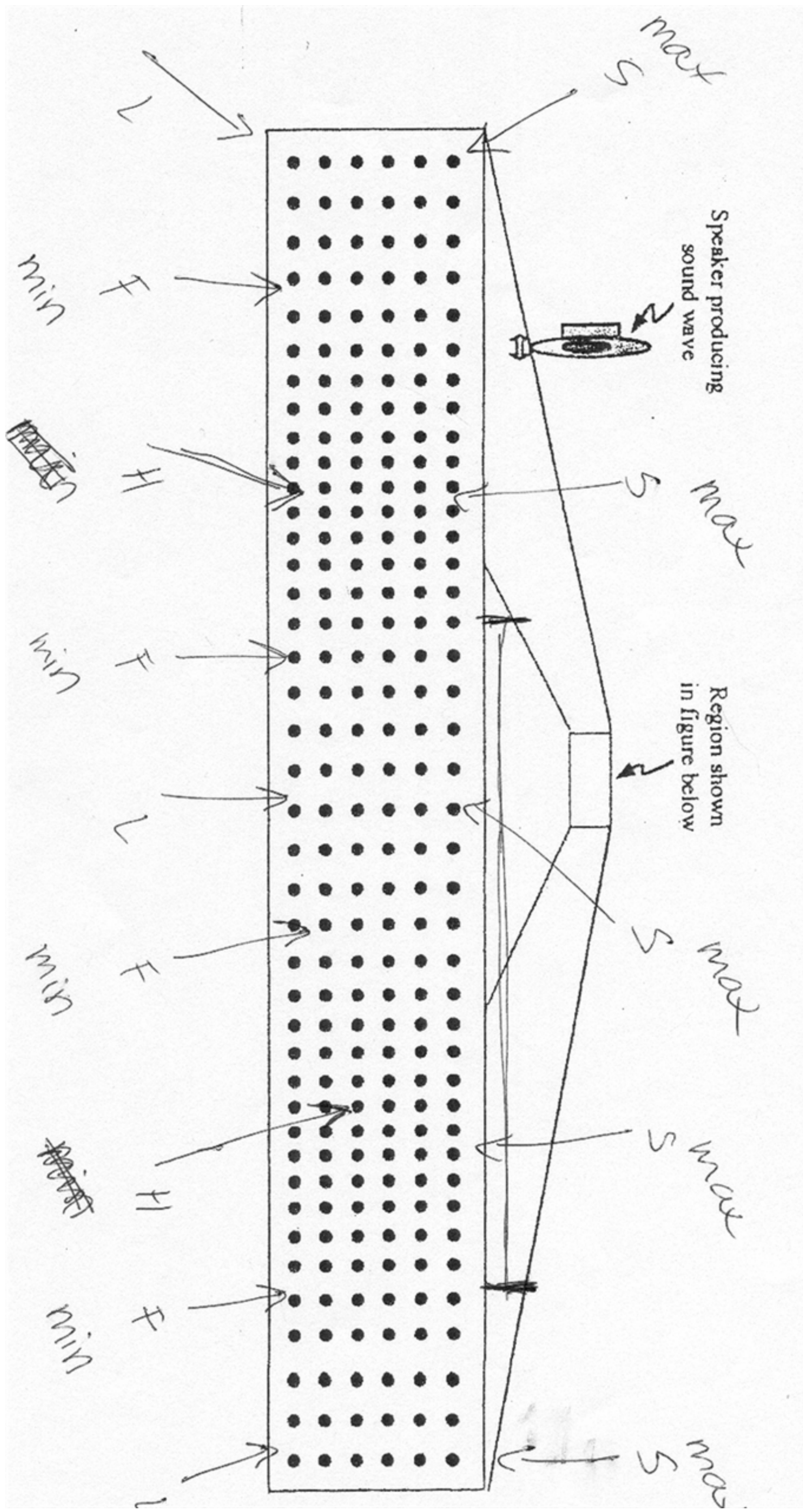


Figure B.4. Mike’s Diagram.

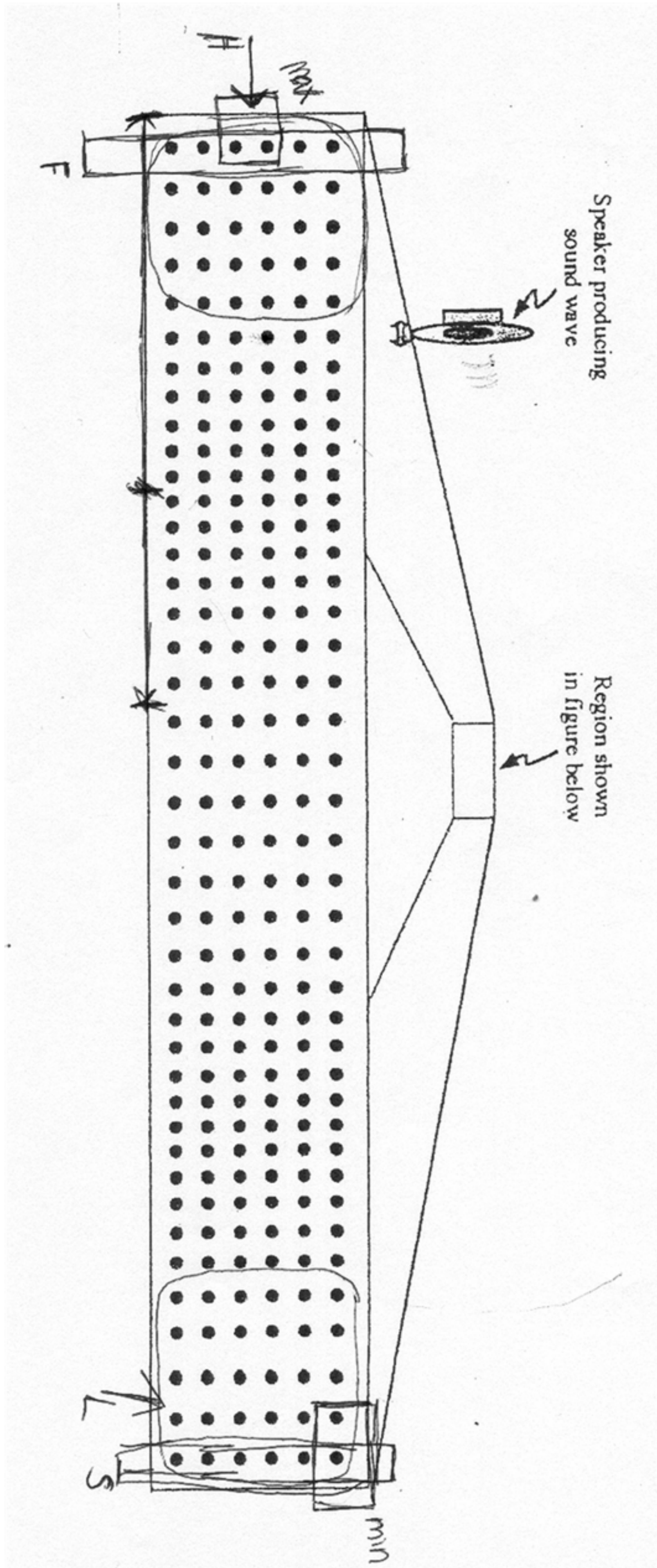


Figure B.5. Sarah's Diagram.

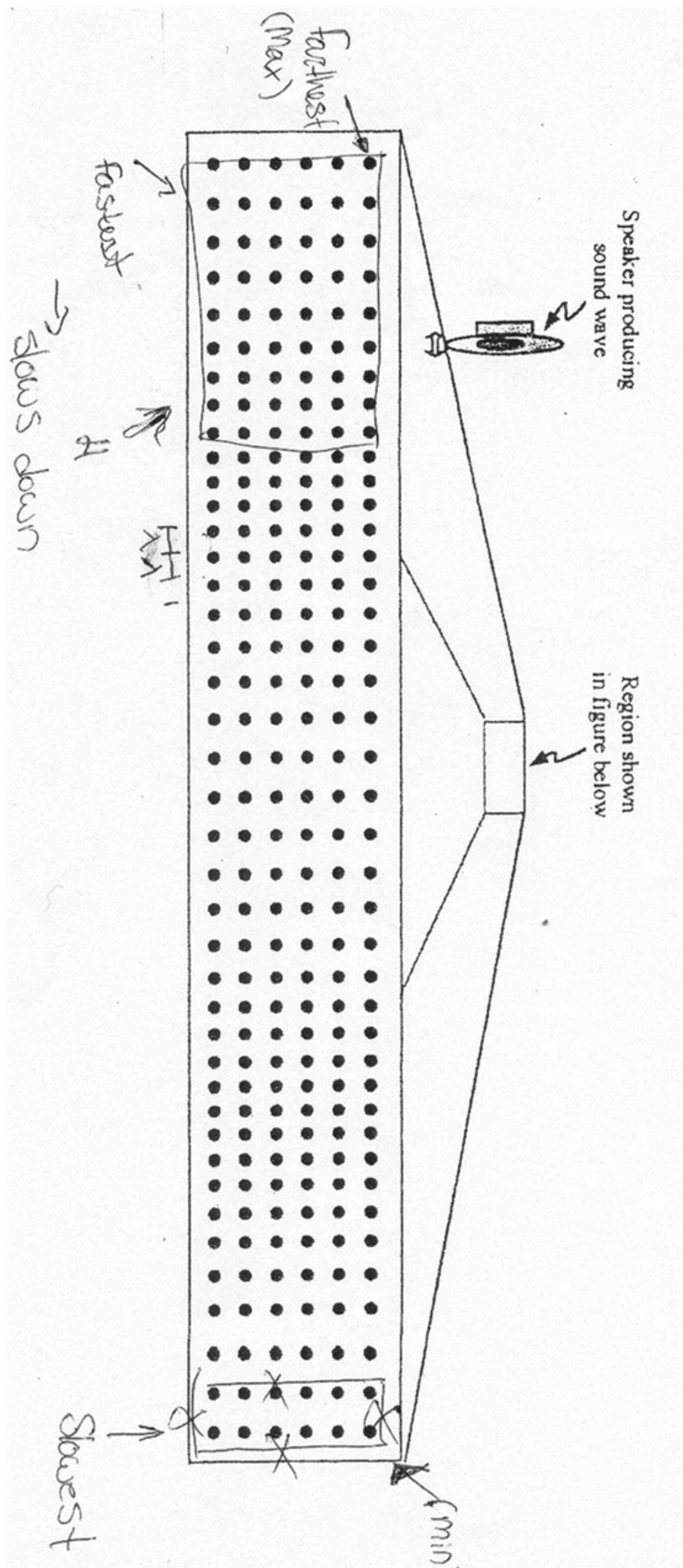


Figure B.6. Julie's Diagram.

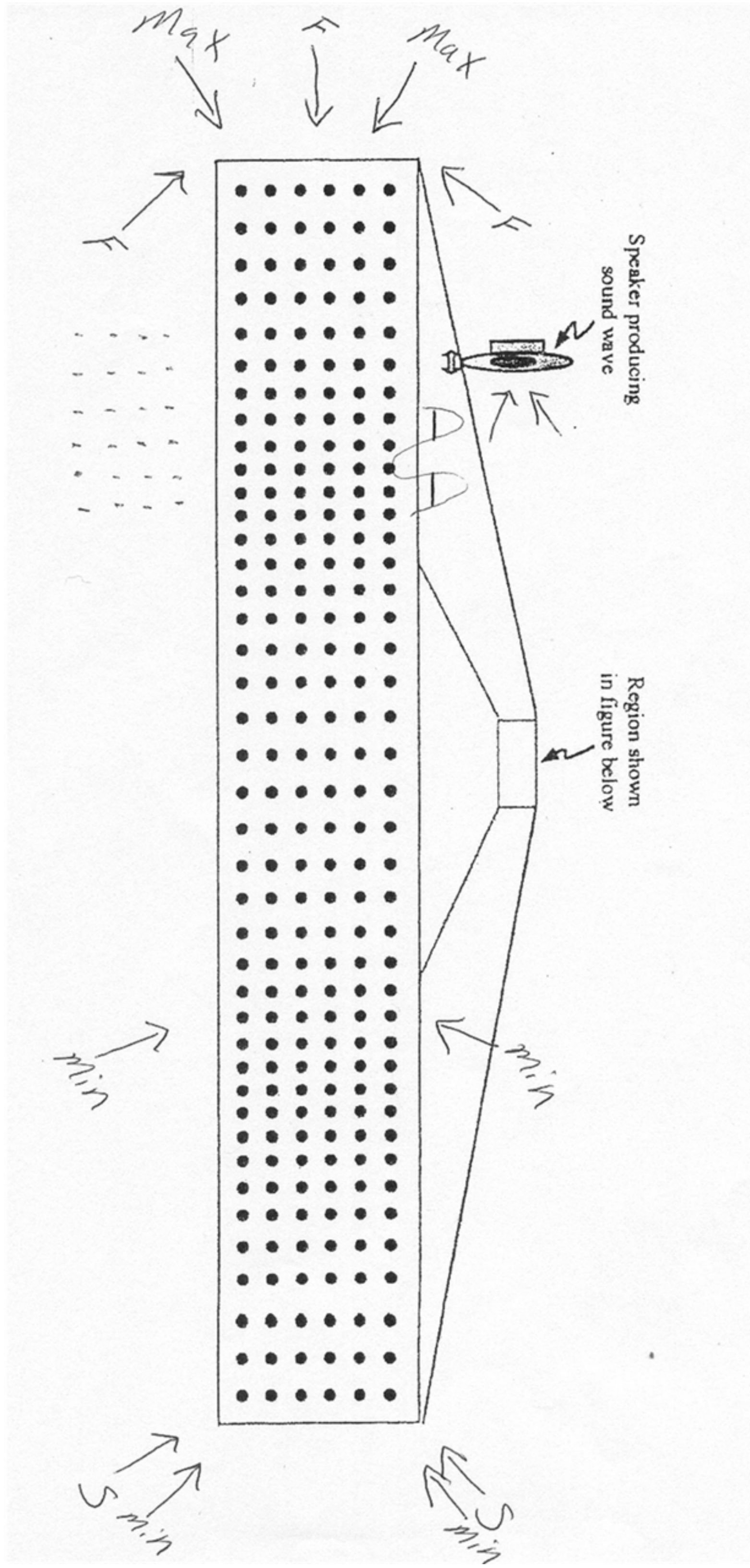


Figure B.7. Tom's Diagram.

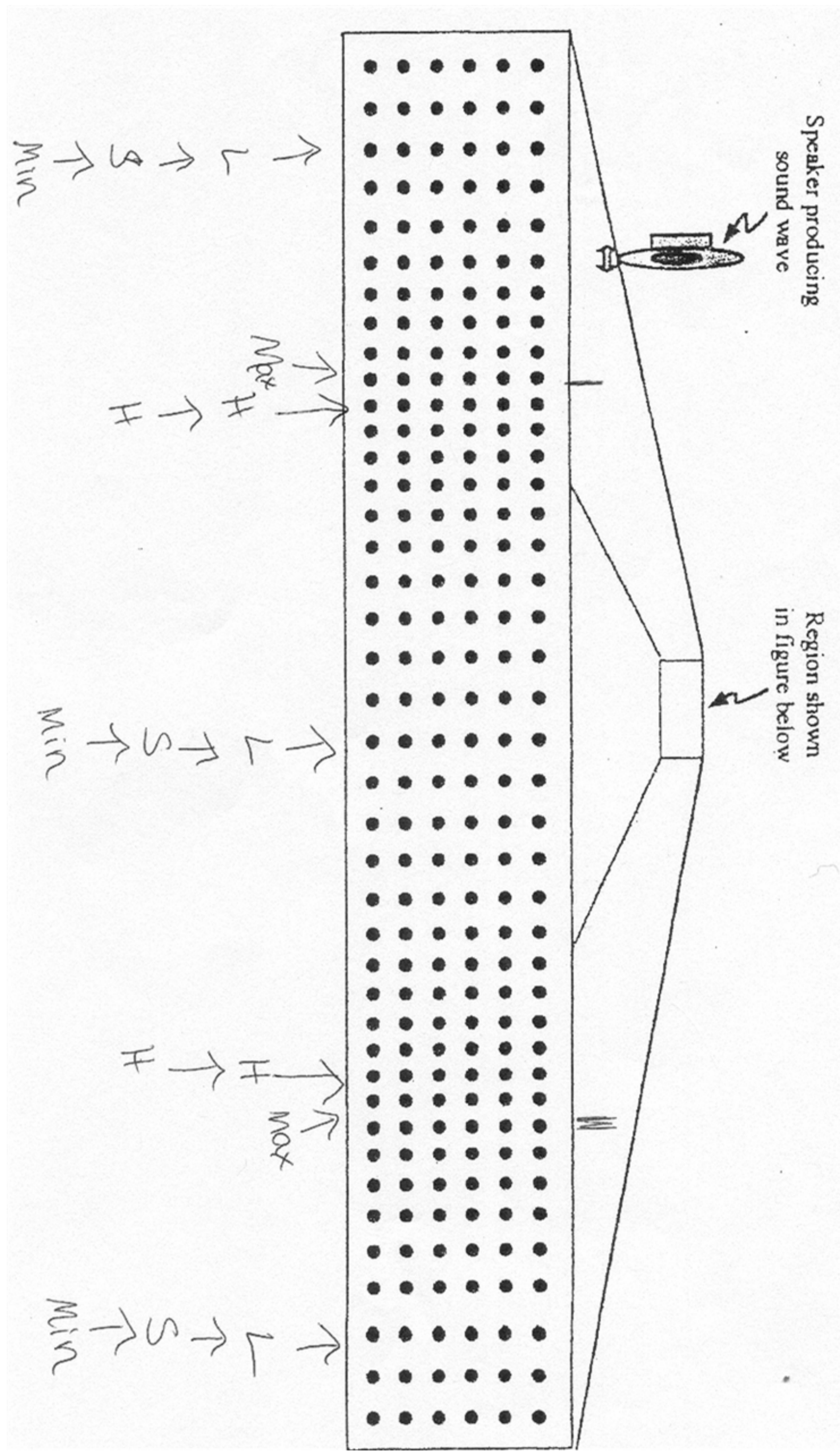


Figure B.8. Cynthia's Diagram.

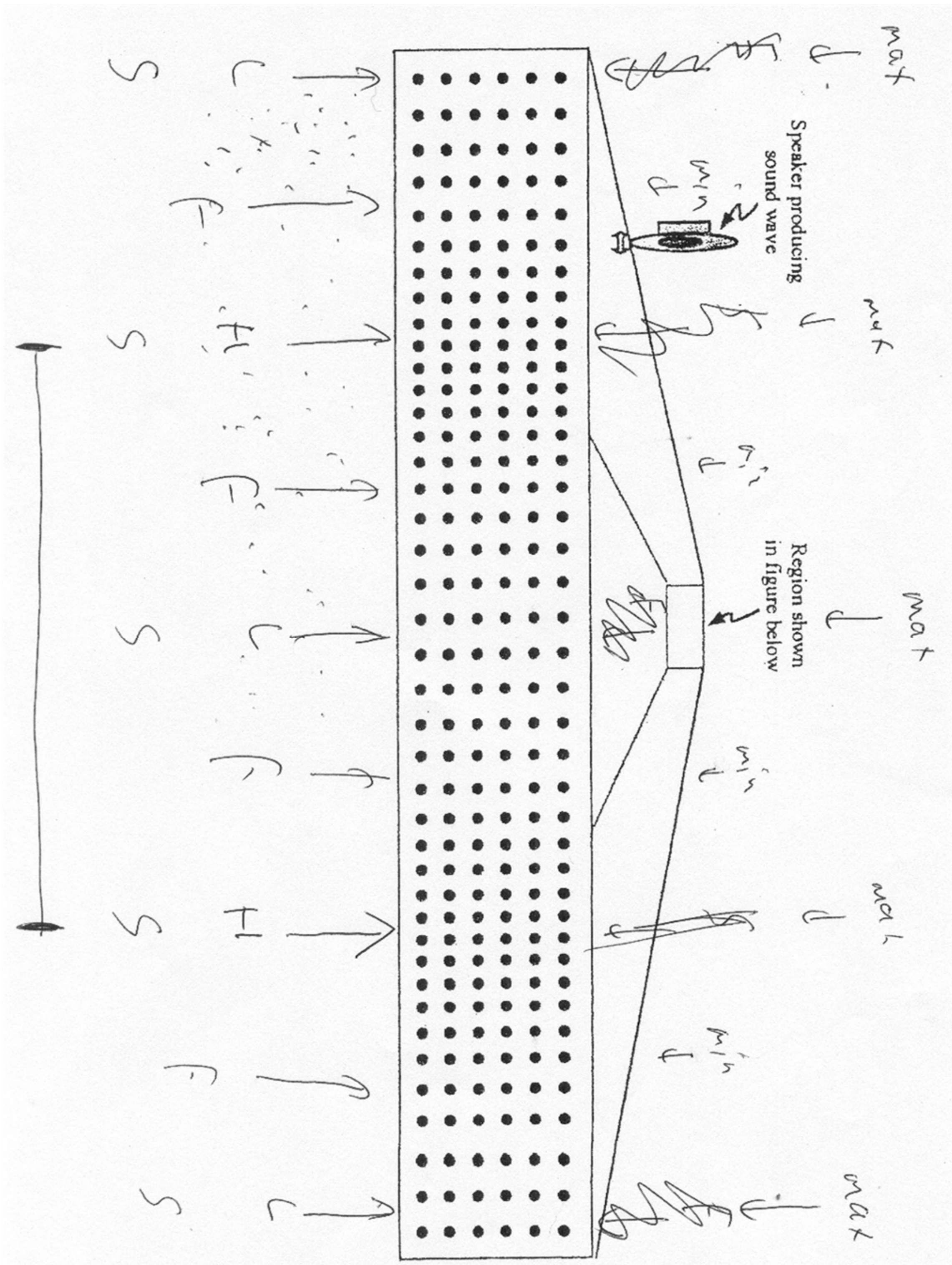


Figure B.9. Richard’s Diagram.

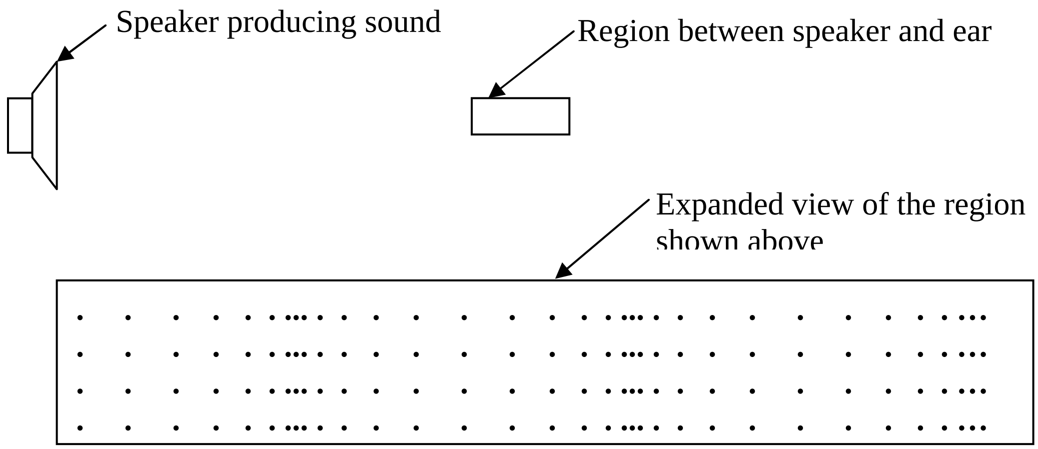
Appendix C

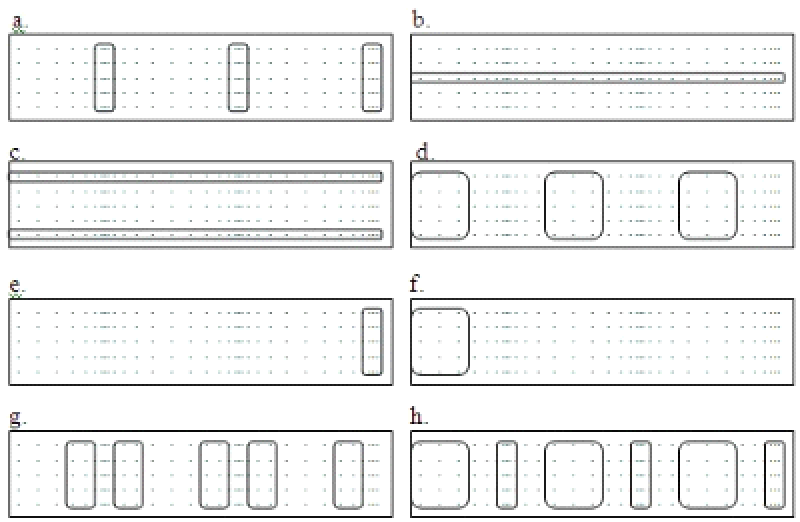
PRETEST: SOUND WAVE PROPAGATION

1. A speaker in a radio converts electrical signals to sound. This is accomplished when the coil in the speaker interacts with the magnet in the speaker
   a. Producing electromagnetic radiation which moves away from the speaker.
   b. Causing the speaker cone to move back and forth creating regions of high pressure and regions of low pressure that move away from the speaker.
   c. Causing the speaker cone to move back and forth pushing air molecules away from the speaker.
   d. Causing the speaker cone to move back and forth pushing air molecules up and down in front of the speaker.
   e. I don't really know how a speaker works.

2. If you could see the air molecules in the path between a radio speaker and your ear, you would see
   a. The air molecules remaining stationary as the sound moves past them.
   b. The air molecules moving back and forth parallel to the direction in which the sound moves.
   c. The air molecules moving away from the speaker and toward your ear.
   d. The air molecules moving up and down perpendicular to the direction in which the sound moves.
   e. I don't really know what the air molecules would do.

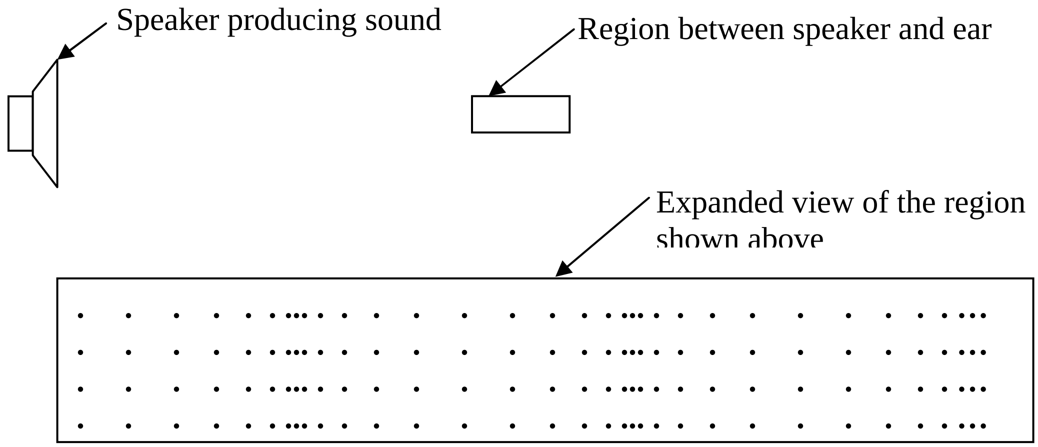
5. The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules. Assume that the region is so small that you can ignore the fact that the sound gets weaker as you get further away from the speaker. Which of the following diagrams has rectangles enclosing the region or regions ***where the pressure is higher than normal atmospheric pressure***? (Note: Full sized diagrams can be found on the last page of this survey.)

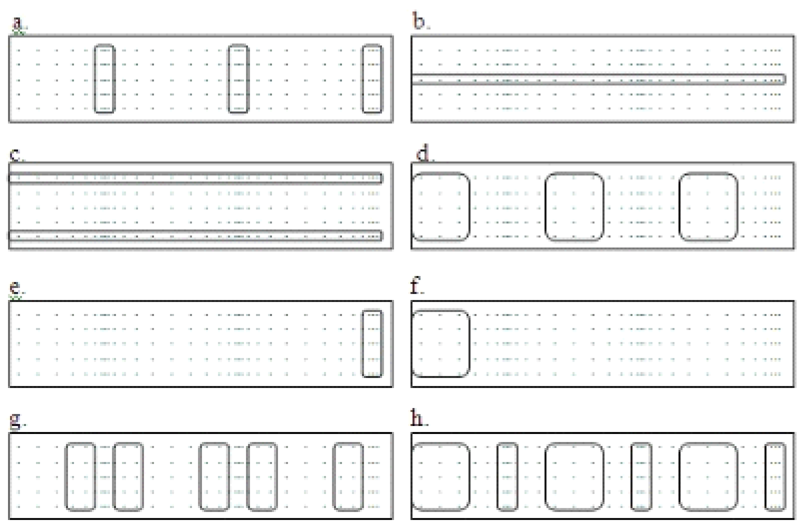




i. There are no areas where the pressure is higher than normal atmospheric pressure. The pressure is the same everywhere.
j. The information provided is insufficient to determine if there are areas where the pressure is higher than normal atmospheric pressure.
k. I cannot answer this question because I don’t understand the diagrams.
l. I don’t know how to determine where the pressure is higher than normal atmospheric pressure.

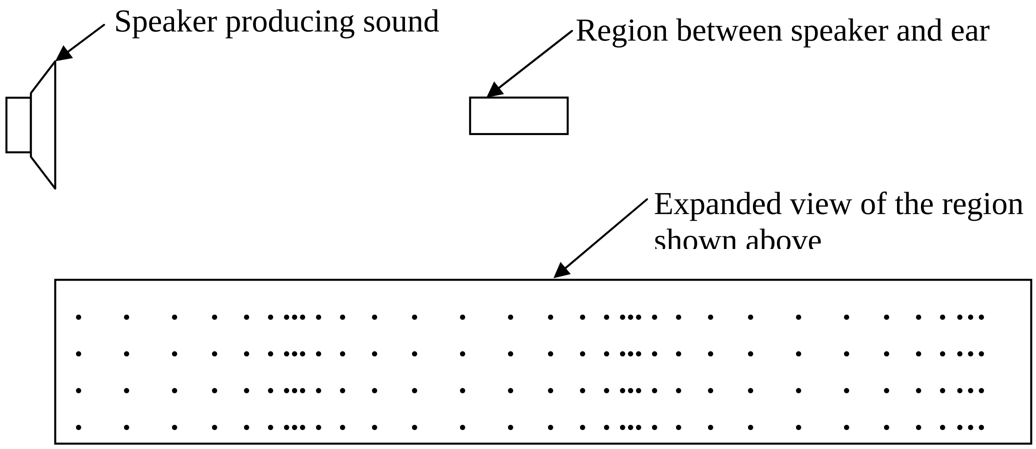
6. The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules. Assume that the region is so small that you can ignore the fact that the sound gets weaker as you get further away from the speaker. Which of the following diagrams has rectangles enclosing the region or regions ***where the air molecules are moving the fastest***?

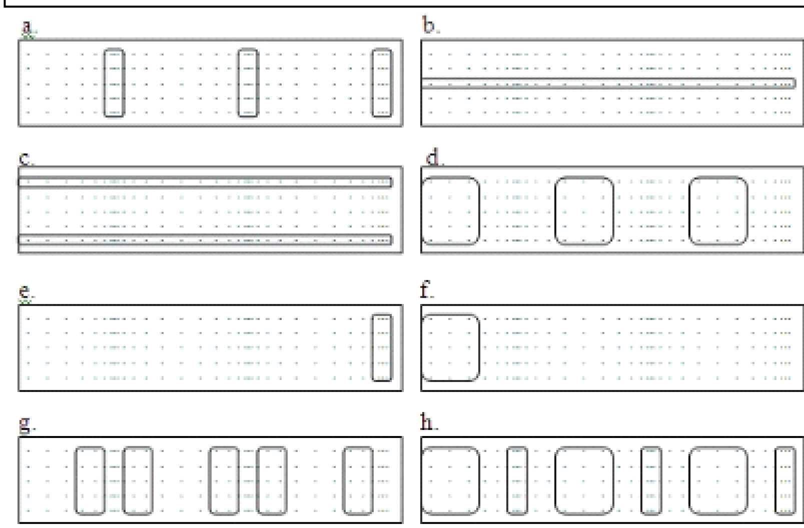




i. There are no areas where the air molecules are moving faster than air molecules in other regions. All of the air molecules have the same speed.
j. The information provided is insufficient to determine if there are areas where the air molecules are moving faster than air molecules in other places.
k. I cannot answer this question because I don't understand the diagrams.
l. I don't know how to determine where the air molecules are moving the fastest.

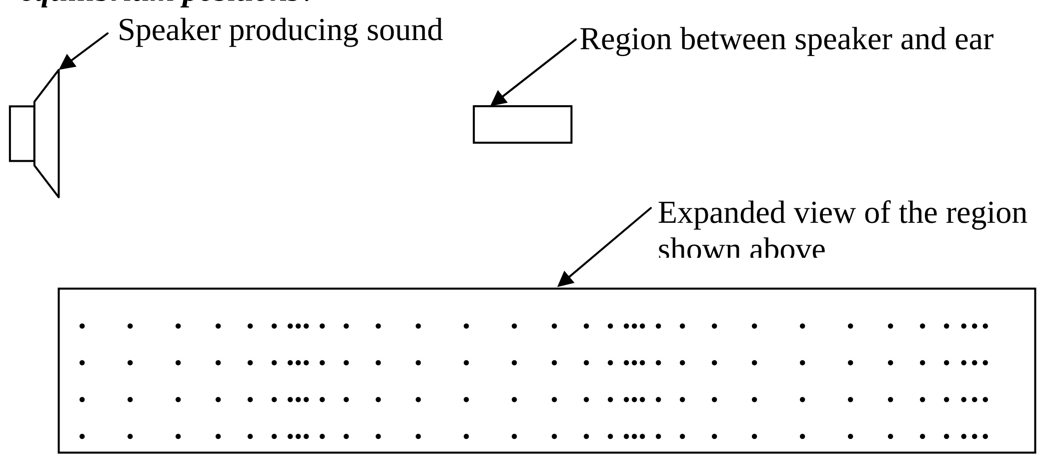
7. The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules. Assume that the region is so small that you can ignore the fact that the sound gets weaker as you get further away from the speaker. Which of the following diagrams has rectangles enclosing the region or regions ***where the air molecules have maximum displacements from their equilibrium positions***?

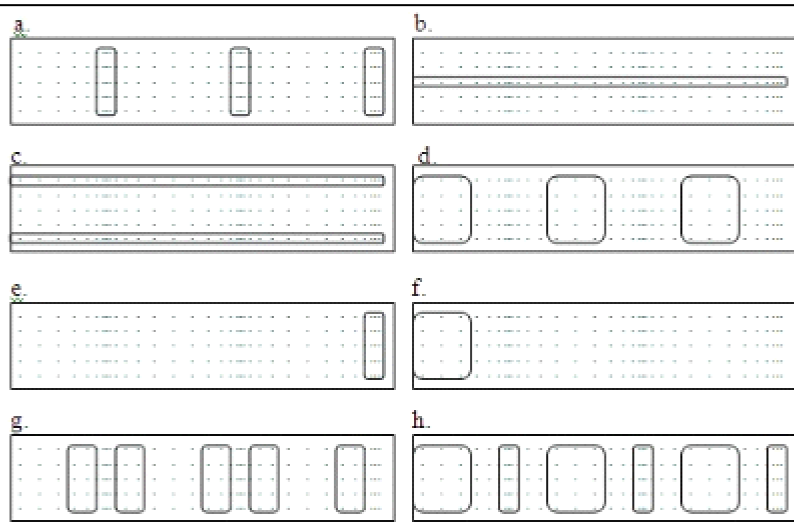




i. All of the air molecules are at their equilibrium positions.
j. All of the air molecules are displaced from their equilibrium positions by the same amount.
k. The information provided is insufficient to determine if there are areas where the air molecules have maximum displacements from their equilibrium positions.
l. I cannot answer this question because I don't understand the diagrams.
m. I don't understand what is meant by "maximum displacement from the equilibrium position".
n. I don't know how to determine where the air molecules have maximum displacements from their equilibrium positions.

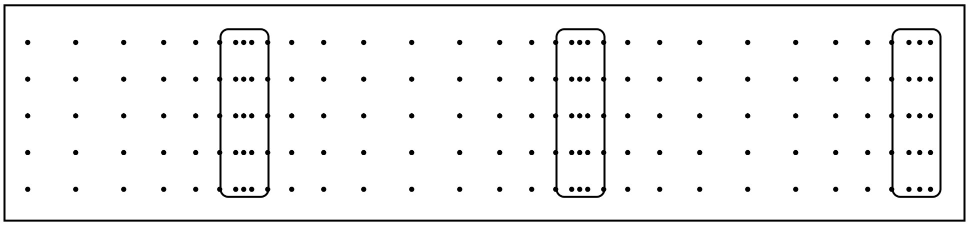
8. The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules. Assume that the region is so small that you can ignore the fact that the sound gets weaker as you get further away from the speaker. Which of the following diagrams has rectangles enclosing the region or regions ***where the air molecules have minimum displacements from their equilibrium positions***?



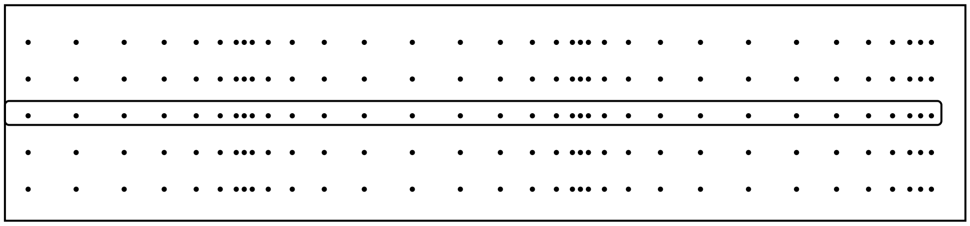


i. All of the air molecules are at their equilibrium positions.
j. All of the air molecules are displaced from their equilibrium positions by the same amount.
k. The information provided is insufficient to determine if there are areas where the air molecules have minimum displacements from their equilibrium positions.
l. I cannot answer this question because I don't understand the diagrams.
m. I don't understand what is meant by "minimum displacement from the equilibrium position".
n. I don't know how to determine where the air molecules have minimum displacements from their equilibrium positions.

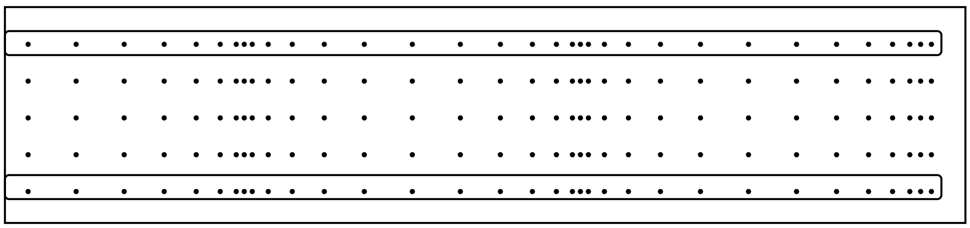
a.



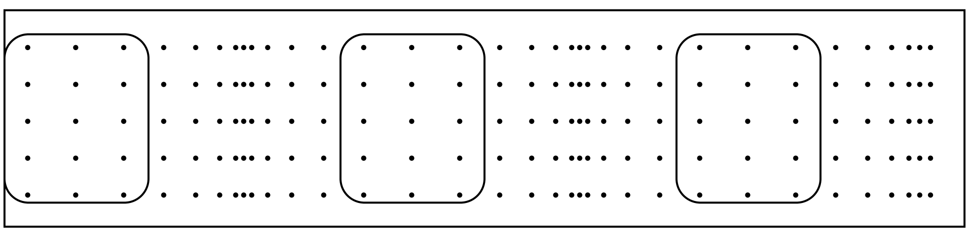
b.



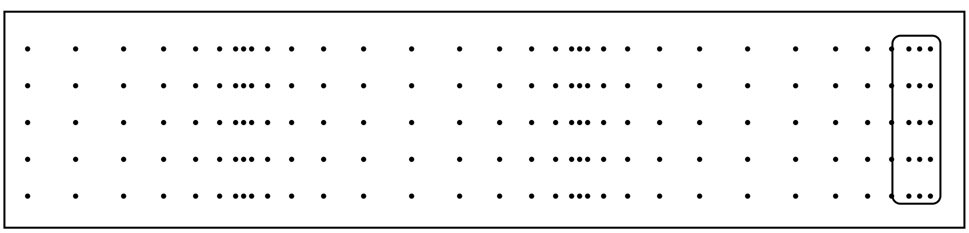
c.



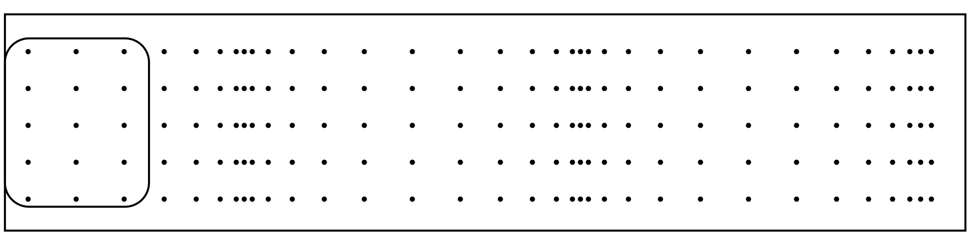
d.



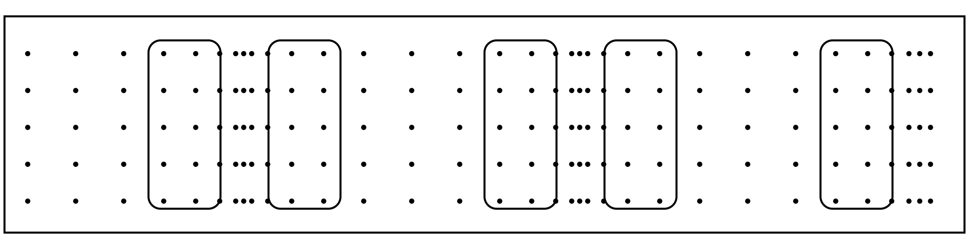
e.



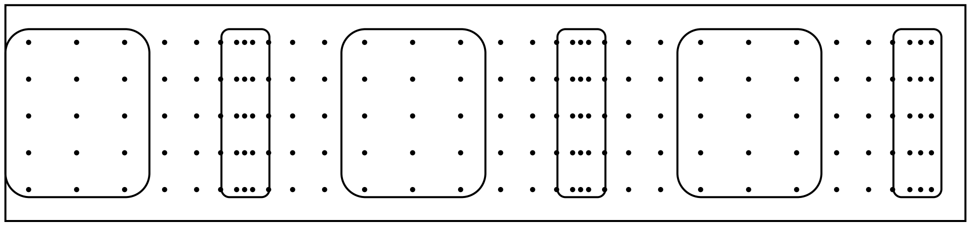
f.



g.



h.

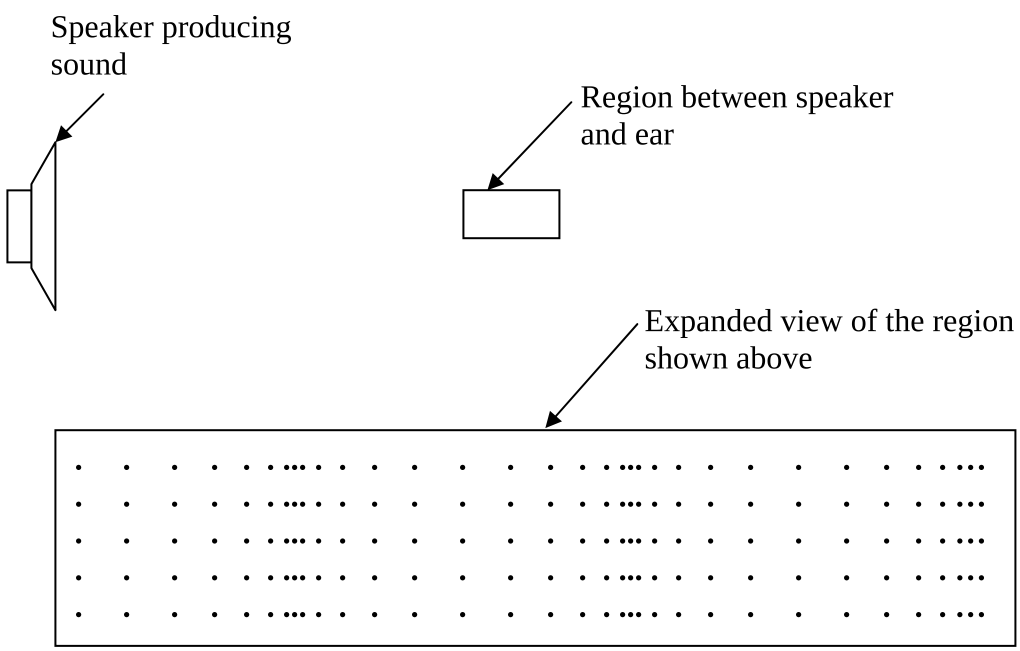


Appendix D

POST-TEST: SOUND WAVE PROPAGATION

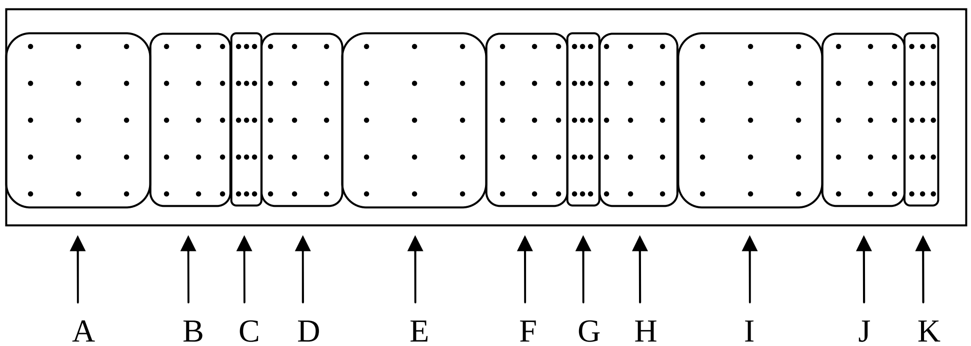
1. A particle of dust is located in front of a radio speaker that is producing a sound with a constant pitch. As you observe the dust particle you notice that it.
   a. Remains stationary as the sound moves past it.
   b. Moves back and forth parallel to the direction in which the sound moves.
   c. Continues to move farther and farther away from the speaker.
   d. Moves up and down perpendicular to the direction in which the sound moves.

The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules. Assume that the region is so small that you can ignore the fact that the sound gets weaker as you get further away from the speaker.

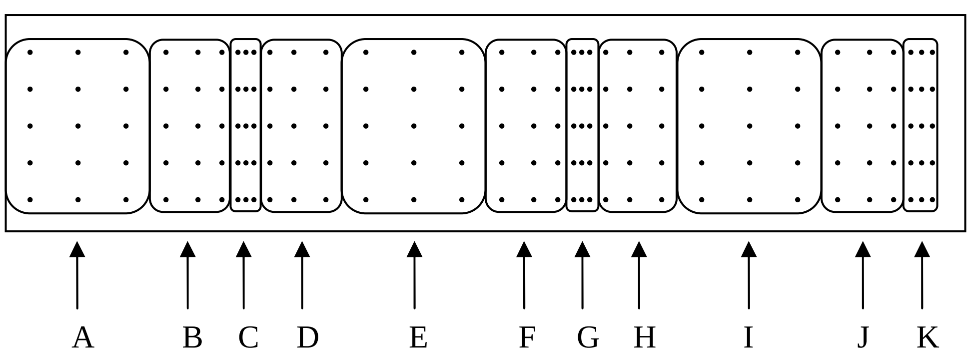


In answering the following questions, consider only the motion caused by the sound and ignore any random motion the air molecules might have.

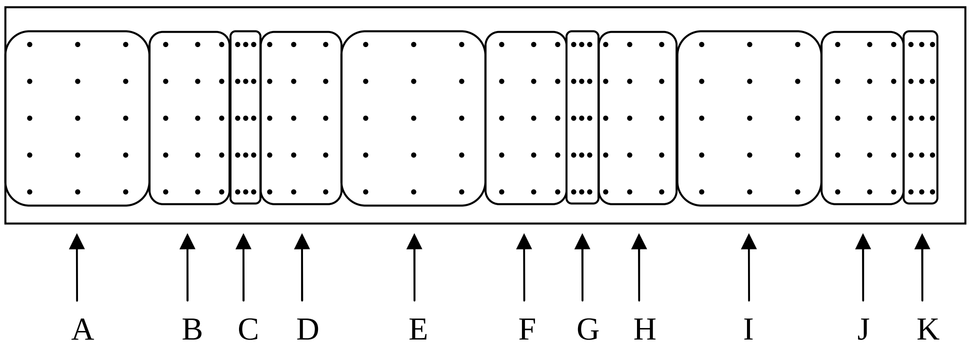
2. Circle the letter or letters in the diagram below that correspond to the region or regions ***where the pressure is lower than normal atmospheric pressure***. Be sure to circle **all** letters that meet this criterion. If none of the labeled areas correspond to places where the pressure is lower than normal atmospheric pressure, draw a circle that encloses a region of low pressure. Draw additional circles if there are other regions of low pressure. Briefly explain how you know.



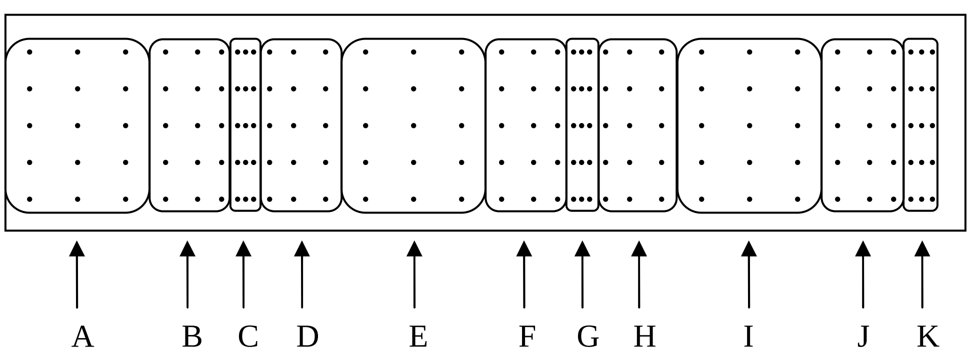
3. Circle the letter or letters corresponding to the region or regions ***where an air molecule would have a velocity with a minimum magnitude***. Be sure to circle **all** letters that meet this criterion. If none of the labeled areas correspond to places where an air molecule would have a velocity with a minimum magnitude, draw a circle that encloses such a region. Draw additional circles if there are other regions that meet this criterion. Briefly explain how you know.



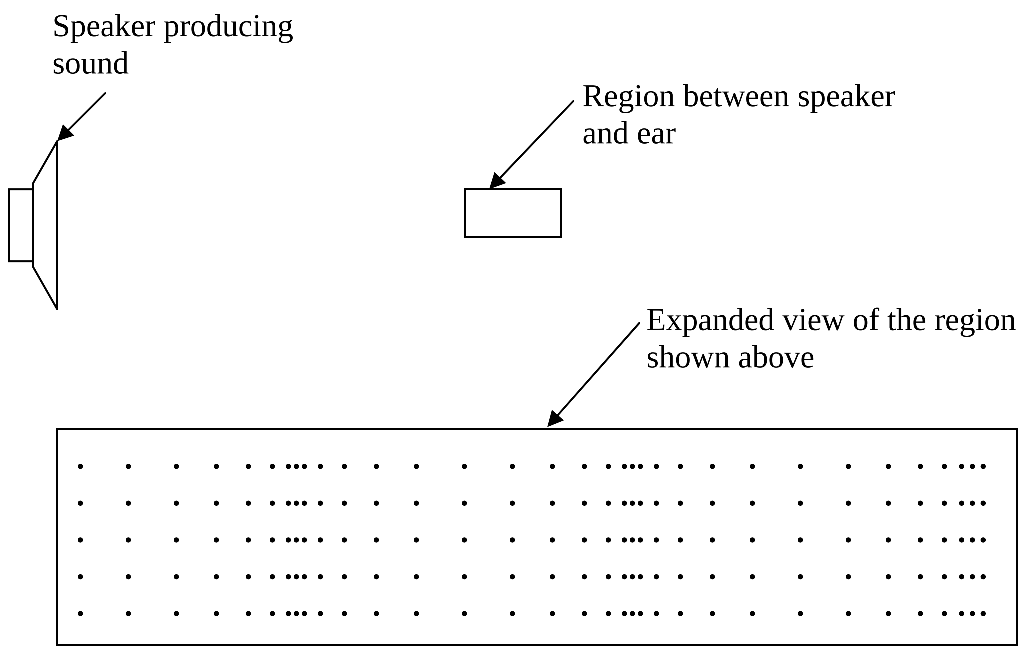
4. Circle the letter or letters in the diagram below that correspond to the region or regions ***where an air molecule would have a displacement from its equilibrium position with a maximum magnitude***. Be sure to circle **all** letters that meet this criterion. If none of the labeled areas correspond to places where an air molecule would have a displacement from its equilibrium position with a maximum magnitude, draw a circle that encloses such a region. Draw additional circles if there are other regions that meet this criterion. Briefly explain how you know.



5. Circle the letter or letters in the diagram below that correspond to the region or regions ***where an air molecule would have a displacement from its equilibrium position with a minimum magnitude***. Be sure to circle **all** letters that meet this criterion. If none of the labeled areas correspond to places where an air molecule would have a displacement from its equilibrium position with a minimum magnitude, draw a circle that encloses such a region. Draw additional circles if there are other regions that meet this criterion. Briefly explain how you know.



6. The diagram below is one that might have been drawn to represent a snapshot of the air molecules in a small region between a radio speaker and your ear as the speaker is producing a tone with a constant pitch. The dots in the expanded view represent individual air molecules.



In the space below, sketch a snapshot of the air molecules in this region a short time (one quarter of the period of the sound wave or less) later.

Briefly explain how you knew to draw the picture above.

Appendix E

LONGITUDINAL WAVE PROPAGATION TUTORIAL

I. Propagation of Sound and Its Effect on the Medium

A. Consider the following discussion among a group of students about how sound travels and interacts with the medium through which it is transmitted.

Student 1: "I think sound passes through air without disturbing the individual air molecules in much the same way that electromagnetic radiation passes through air without disturbing the air molecules."

Student 2: "But I thought that as sound passes through air, it causes the air molecules to move up and down, perpendicular to the direction in which the sound wave is traveling. I picture the motion of the air molecules as being similar to the motion of the individual coils of a spring as a transverse wave moves along the length of the spring."

Student 3: "That doesn't sound quite right to me. I agree that the air molecules move, but I think they move back and forth parallel to the direction in which the sound wave is traveling. I think their behavior is more like the behavior of the individual coils of a spring as a longitudinal wave moves along the length of the spring."

Student 4: "If that's right, how does the sound get to your ear? I think the sound wave has to push the air molecules toward your ear in order for you to hear it. The source of the sound must act like a fan, pushing the air molecules away from it."

Discuss the ideas that these four students have with your group. Do you agree with any of these students? If so, state which one. If not, describe your group's model for sound propagation.

B. Imagine a soap bubble floating in air in front of a speaker that is producing a sound with a low, constant pitch. Discuss your ideas about the motion of the soap bubble with your group. How do you think each of the four students would describe the motion of the soap bubble? Describe your group's thinking about the motion of the soap bubble.

1. Student 1

2. Student 2

3. Student 3

4. Student 4

5. Your Group's Model

C. View the video clip of the soap bubble in front of the speaker (Bubble.mpg). Describe the actual motion of the soap bubble.

D. Which student's description best accounts for the behavior of the soap bubble? Explain how you decided.

II. Simple Harmonic Motion

A. The passage of a sound wave through air superimposes simple harmonic motion on the random motion of the air molecules making up the medium through which it is being transmitted. This is similar to the motion of the simple system consisting of a mass and two springs shown at right.

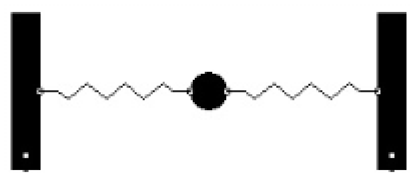


Figure 1

B. View the video clip ***Mass and Springs.avi.***

C. In the boxes below the figures, draw Free Body Diagrams for the mass when it is in each of the positions shown below during the animation, and determine the net force in each case. Neglect the force of gravity..

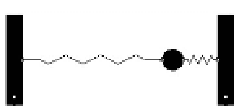


Figure 1-1

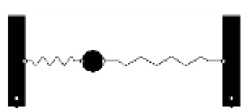


Figure 1-2

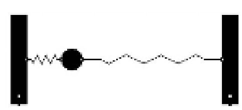


Figure 1-3

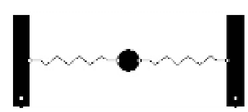
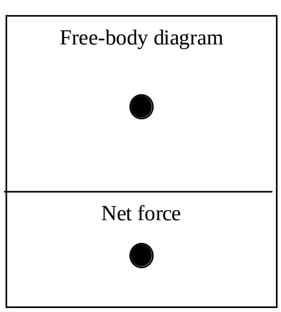
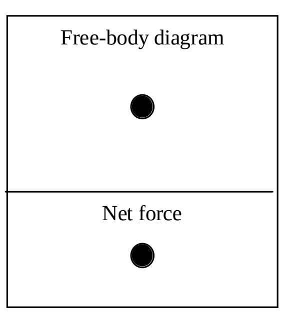
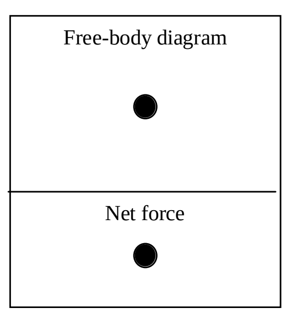
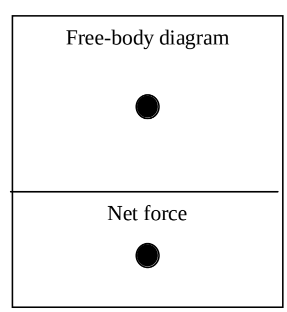


Figure 1-4









D. Use the table below to organize information about the motion of the mass in the video clip. Enter the locations where the *magnitudes* of the net force, acceleration, and velocity have their maximum and minimum values.

	Magnitude of Net Force	Magnitude of Acceleration	Magnitude of Velocity
Maximum			
Minimum			

1. How did you decide where the magnitude of the net force was a maximum and where it was a minimum?

2. How did you decide where the magnitude of the acceleration was a maximum and where it was a minimum?

3. How did you decide where the magnitude of the velocity was a maximum and where it was a minimum?

4. Do you notice any relationship between the position, speed, acceleration, and net force for the mass? For example, do the maximum magnitudes of these values all occur at the same position, or is there a different relationship?

III. Modeling a Longitudinal Wave

Now consider a series of particles separated by springs. Suppose that this arrangement has been set in motion by pushing the leftmost particle to the right, pulling it back to the left, then repeating this action.

View the video clip ***Simulated Longitudinal Wave.avi***. Carefully observe the motion of one of the masses in this arrangement.

A. Compare the motion of this mass to the mass in the previous video clip.

B. The black markers indicate the equilibrium positions of the particles. Pause the video clip at a point where one of the particles is at its equilibrium position.

   1. Is the magnitude of the **net force** on the particle *maximum*, *minimum*, or *neither* when it is located at its equilibrium position? Explain.

   2. Is the magnitude of the particle's **acceleration** *maximum*, *minimum*, or *neither* when it is located at its equilibrium position? Explain.

   3. Is the magnitude of the particle's **velocity** *maximum*, *minimum*, or *neither* when it is located at its equilibrium position? Explain.

   4. Look at the spacing between the particle at the equilibrium position and the adjacent particles. How does the spacing of the particles in this case compare to the equilibrium spacing?

C. Stop the video clip in several other places and examine the spacing of another mass that is at its equilibrium position.

   Do you find that the spacing of the particles is always the same when the center particle in a cluster is located at its equilibrium position? If not, what are the possible spacings when the particle is at its equilibrium position?

D. Regions of a longitudinal wave where the particles of the medium are closely spaced are called ***compressions***; areas where the particles are widely spaced are called ***rarefactions***.

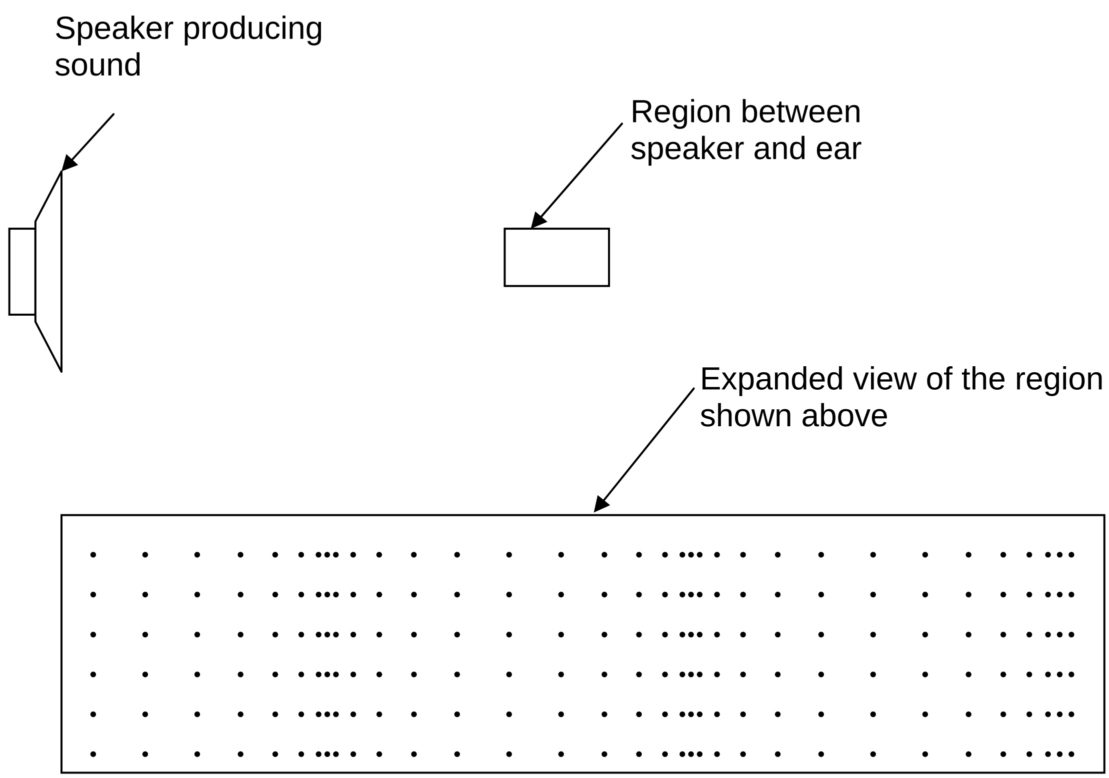
   How would you describe the region near a particle at its equilibrium position?

E. Summarize your observations concerning particle spacing, net force, acceleration, velocity, and displacement of the particle from its equilibrium position.

IV. Sound Waves in Air

A. Air molecules are not connected by little springs: however they do behave in the same way that the particles in the longitudinal wave model behave. The figure below represents an idealized representation of the positions of the air molecules as a sound wave is traveling through a small region in front of the speaker. This diagram ignores the random spacing and motion of the individual air molecules that would be present in an actual sample of air in front of a speaker. Places where the dots are close together represent compressions and places where the dots are farthest apart represent rarefactions.

Ask your instructor for a full-page version of this figure, and use that sheet as a group to answer the questions on the next page before marking your sheet.



1. Circle the places in the diagram where you think **the air pressure is higher than normal atmospheric pressure**. Label these areas **H**.

2. Circle the places in the diagram where you think **the air pressure is lower than normal atmospheric pressure**. Label these areas **L**.

3. Circle the places in the diagram where you think **the air pressure is at normal atmospheric pressure**. Label these areas **A**.

4. Explain how you decided on these locations.

5. Circle the places in the diagram where you think **the air molecules are displaced from their equilibrium positions by the minimum amount**. Label these areas **Min**.

6. Circle the places in the diagram where you think **the air molecules are displaced from their equilibrium positions by the maximum amount**. Label these areas **Max**.

7. Explain how you decided where the molecules had their maximum and minimum displacements.

8. Draw arrows that point toward places in the diagram where you think **the air molecules are moving the fastest**. Label these areas **F**.

9. Circle the places in the diagram where you think **the air molecules are moving the slowest**. Label these areas **S**.

10. Explain how you decided where the air molecules were moving the fastest and where they were moving the slowest.

Describe the relationship between the pressure and the displacement in the sound wave. Specifically, are the locations of the maximum *displacement* of the particles the same locations as the maximum *pressure*? If not, what are the corresponding values of the other quantity for those locations?

BIOGRAPHY OF THE AUTHOR

Earl Coombs was born in Philadelphia, Pennsylvania on January 5, 1947. He graduated from Rockland District High School in 1964. He attended the University of Maine and received a Bachelor's Degree in Education in 1968, and a Master's Degree in Educational Administration in 1985.

After completing his undergraduate degree in 1968, Earl taught physics at Marshwood High School in Eliot, Maine for one year before being called to active duty. He served for three yeas as Logistics Staff Officer and Logistics Plans Officer with the U.S. Army Engineer Command in Frankfort, Germany.

Upon returning to the United States, Earl taught math and science for four years at Rangeley High School, biology and physics for eight years at Van Buren District Secondary School, and physics for twelve years at Winslow High School. He is currently the Physics and Chemistry Instructor at Kennebec Valley Community College.

Earl was the Presidential Awardee in Science Teaching from Maine in 1989 and received a National Educator Award in 1995. He is a candidate for a Master of Science degree in Physics from the University of Maine in December 2007.