AN INVESTIGATION INTO STUDENT UNDERSTANDING OF LONGITUDINAL STANDING WAVES

by

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TABLE OF CONTENTS

1. INTRODUCTION 1

What do We Want Our Students to Learn? 1
Subject Matter 1
Other Learning Goals 2
Why Sound? 3

2. LITERATURE REVIEW 6

Paradigms and General Comments on the Teaching and Learning of Physics 6
Understanding Constructivism 6
Teaching by Telling is Ineffective 8
Large-scale Knowledge Structures 8
Fine-Grained Knowledge Structures 9
Prior Work in Student Understanding of Sound and Waves 12
Mechanical Waves 13
Models of Sound and Sound Propagation 18

3. DEVELOPING THE STANDING WAVE DIAGNOSTIC TEST 22

The Genesis of the Project 22
Exploring Student Difficulties: Preliminary Introductory Physics Surveys 24
Physics 211, Fall 2003 24
Physics 206 and 211, Spring 2004 28
Exploring Student Difficulties: Examination Questions 31
Student Interviews 34
The Standing Wave Diagnostic Test 38
Topics Addressed 40

4. STANDING WAVE DIAGNOSTIC TEST: ADMINISTRATION AND RESULTS 42

Interpretations of the Data 43
Overall Score on the SWDT 43
Individual Question Performance - Examples 46

5. LONGITUDINAL STANDING WAVES TUTORIAL DEVELOPMENT 51

Rationale for Choosing Tutorial-Style Instruction 51
Overview of the Longitudinal Standing Waves Tutorial 52
Issues Addressed in the LSW Tutorial 54
Visualization of Longitudinal Standing Waves 54

TABLE OF CONTENTS - CONTINUED

Air Column Resonance and Particle Motion 56
Pressure 57
Resonance as a Special Condition 58
Representations of Longitudinal Standing Waves 58
Homework 60

6. CURRICULUM IMPACT ON STUDENT LEARNING 62

Post-instruction Results from the Treatment Section 62
Performance on SWDT 62
Individual Question Performance: Examples 63
Anecdotal Evidence for Learning 67

7. CONCLUSIONS 69

What are the Main Student Difficulties in Understanding Longitudinal Standing Waves? 69
What Can Be Done to Impact Student Understanding? 70
In Conclusion 71

REFERENCES CITED 72

APPENDICES 76

APPENDIX A: Survey Instruments 77
APPENDIX B: Physics 211 Exam Questions, Spring 2004 88
APPENDIX C: Standing Wave Diagnostic Test 91
APPENDIX D: Longitudinal Standing Waves Tutorial and Homework 96

LIST OF TABLES

Table Page

1. Summary of Results from Spring 2004 Physics 211 Exam Questions, Post-instruction....33

2. Physics 206 Pre-instruction Overall Scores on an Abbreviated SWDT....44

3. Fall 2006 Physics 206 Post-instruction Scores....45

4. Fall 2006 Physics 206 Scores on Individual Questions, Post-instruction. (N = 128)....47

5. Fall 2006 Physics 206 Post-instruction Responses to SWDT Questions 12, 16, 17, 18. (N = 128)....48

6. Physics 206 Post-instruction Overall Performance on the SWDT, Treatment and Non-treatment Sections....63

7. Spring 2006 (treatment) and Fall 2006 (Non-treatment) Physics 206 Scores on Individual Questions, Post-instruction....64

8. Answer Distribution (Percentages) for SWDT Question 13, Post-instruction....66

9. Answer Distribution (Percentages) for SWDT Question 6, Post-instruction....67

LIST OF FIGURES

Figure Page

1. Hybrid Picture of a Standing Wave in a Pipe 38

ABSTRACT

This study investigates the difficulties that introductory university physics students have with the concept of longitudinal standing waves in the context of standing waves in pipes. My goal is to identify difficulties that persist even after standard instruction on longitudinal standing waves and attempt to improve upon that method of instruction. The study follows a four-step design. I first use exploratory surveys and interviews with students to elicit the difficulties present in students' understanding of longitudinal standing waves in pipes. I then use the information gained to create and assessment instrument, the Standing Waves Diagnostic Test, and a curricular intervention, the Longitudinal Standing Waves Tutorial. I then undertake a three-step process of pre-testing students with the Standing Wave Diagnostic Test, intervention with the Longitudinal Standing Waves Tutorial, and post-testing again with the Standing Wave Diagnostic Test to determine the impact of the intervention. This is then compared to data from students in classes where the intervention is not used. Students using the intervention significantly outperform their non-intervention counterparts on the Standing Wave Diagnostic Test. The results of the students pre- and post-tests indicate that significant improvement in students' understandings of longitudinal standing waves can be achieved by the use of the tutorial.

CHAPTER 1

INTRODUCTION

What do We Want Our Physics Students to Learn?

The introductory physics sequence at most colleges and universities in the United States is in large part structured the same way from one school to the next. In schools with a semester-based curriculum, it is common to have a two-semester sequence of physics. It is also common to have a calculus-based version of the class, primarily for students majoring in physics and engineering, and an algebra-based version of the class primarily for a broader group of majors – anything from biology to architecture to pre-pharmacy. The distinction between these classes is generally the freedom to use calculus – primarily integrals and derivatives – to explain the mathematical construct of equations and formulae in physics. However, the actual physics content in these two parallel tracks is similar, and in some cases identical. The ultimate question is, what do we want our students to learn? What do we want them to know once they walk out of the classroom?

Subject Matter

There are some subjects that are almost universally agreed upon. The basics of mechanics, such as kinematics, dynamics, momentum and energy conservation, and rotational motion are taught in virtually every first-semester course, independent of whether the course is algebra-based or calculus-based. Likewise, electricity and magnetism concepts are generally taught as a second-semester topic. While the teaching

approaches can vary quite significantly, different instructors at different schools teach many of the same topics and have a similar goal of subject competence at the end of the term.

Other topics are less agreed upon. Subjects such as optics, fluid mechanics, waves, sound, heat and temperature, and atomic physics are sometimes left out by instructors. Others teach their course in a way to cover all of the above. Even if instructors do cover the same subjects, they may shuffle them into different orders and even different semesters. The subject of this thesis, sound, is one of those less-agreed-upon subjects. Some instructors include it as a first-semester topic and others leave it until the second semester. Others may skip it altogether, or may narrow it to only discuss mechanical waves on a string or the decibel scale of sound intensity.

Other Learning Goals

Students often raise the question, "Why do I have to take this class if I'm never going to use it again?" The second portion of that statement varies in applicability from student to student. I would not agree with any student that they will never use physics again; it is after all a part of their everyday life. But their point is understood: in their future endeavors, one would expect that physics majors would be more likely than botany students (or any number of other examples) to use subject matter covered in their introductory course.

But in addition to the content knowledge instructors expect students to gain from our physics courses, we often have additional goals for our students. One of the major goals instructors have, whether stated explicitly or not, is development of problem-

solving and/or critical thinking skills. This could be described as developing the thought processes of students to be better equipped to comprehend problems that they have never seen before. Critical thinking skills are broadly applicable, and are often touted by professors in non-physics disciplines as one of the main reasons their department requires its majors to take physics. Critical thinking manifests itself in many ways, but I liken it to the difference between the blind application of a concept, formula, or pattern, and the understanding of how to determine what appropriate constructs could be used. Problem solving skills are closely related to critical thinking skills, directly using that thought process to reason through a problem whose solution is not immediately obvious.

Why Sound?

So why bother investigating students' understanding of sound when it may not be a portion of the physics content students may use in the future, and is a subject that not all instructors choose to cover in much detail? I go back to ideas about critical thinking. The concept of sound can be (and frequently is) taught in a way that does not encourage critical thinking. While we can give very lucid, interesting, and sense-making lectures on the topic, the student's true engagement in the topic comes through their own work, primarily in the form of homework problems and labs. Students can often be successful in answering textbook questions about sound by simply hunting for a formula and inserting numbers. They may have to memorize, for example, which formula is for the open-open pipe and which is for the closed-open pipe. But that hardly qualifies as critical thinking. Linking the mechanics of the motion of the medium to changes in pressure

allows students to have a picture of why things are the way they are inside a pipe. Rather than guessing or memorizing, they can *reason* whether there is a displacement node or antinode at the closed end of a pipe. Despite all the things we may *say* at the front of the classroom, it is what students *do* that truly impacts their understanding. If they are not put into a position where they must reason through the physics, understanding sound may simply become "pattern matching" to them.

Sound is also a topic in which a simplified model of the actual physical activity can be very useful. We should remember that every model, however thorough, is incomplete. From longitudinal models of sound to wave-particle duality models of light, models are approximations of reality that allow us to understand physical processes. Using the curriculum produced as a part of this work, students develop an understanding of standing waves in air using a simplified model that involves purely longitudinal motion. The reality is that this motion is superimposed on random thermal motions which are greater in magnitude. While it is true that the deepest understanding of particle motion comes from considering both of these factors, I have seen in my work with students that an understanding of longitudinal standing wave motion can be achieved without including the additional details of random thermal motion. The simplified model, while incomplete, is pedagogically worthwhile. Through interviews with students and through observation of student discussions in the classroom, it is apparent that students do not draw upon ideas of random thermal motion to describe longitudinal standing wave phenomena. Random thermal motion simply doesn't come up in

discussion and thus doesn't cause problems when students use the purely longitudinal model.

In the following chapters I will describe an investigation into students' understanding of sound that gets beyond that "pattern matching" level. In Chapter 2, I will describe the literature that is appropriate to the teaching and learning of sound and longitudinal standing wave concepts. The creation of the Standing Wave Diagnostic Test, a test useful in assessing students' understanding about longitudinal standing waves in pipes, is described in Chapter 3, and pre-instruction results from that diagnostic are presented in Chapter 4. The preparation of a tutorial as an attempt to improve instruction and some of the results of that instruction are described in Chapters 5 and 6, followed by concluding remarks in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

This literature review is divided into two main sections. The first describes the general background of physics education research as it applies to this thesis. The second highlights specific physics education research done in the area of students' understanding of sound, particularly those studies more applicable to this work. There is a comparatively small amount of literature regarding students' concepts of sound as compared to other topics such as electric circuits or Newton's Laws.

Paradigms and General Comments on the Teaching and Learning of Physics

In order to discuss ways in which to impact a student's learning process, we must first recognize that we can view the learning process with a variety of lenses. Assumptions that we make about the learner affect what approaches we might take in impacting instruction.

Understanding Constructivism

One way to view the learning process, and the view commonly taken in most physics education research, is to use constructivism as a basis for interpreting how students learn. "Constructivism" has a range of definitions, but a paraphrase of McDermott (1991) says it quite simply: The constructivist view of how scientific knowledge is obtained states that each individual must create his or her own concepts, and any pre-existing knowledge he or she may have significantly affects what he or she

can learn. The student is effectively a creator of his/her concepts, not simply a recipient of those concepts. The student's mind is not a blank slate. Rather, anything an instructor wishes to teach must take into account the necessity of making modifications to the student's pre-existing information.

The first main idea is that knowledge is something that is *constructed* by the individual, not *transmitted* from one person to another. In other words, the things that are truly learned by a student depend fundamentally on the student's own ability to put together the building blocks of a concept and create that knowledge for himself or herself. We are unable to simply "give" the knowledge to the student as one would upload information from a portable flash drive storage device to a computer hard disk.

In the computer's case, what is already present on the computer doesn't affect the ability to transfer information from the portable drive to the computer (as long as there is free space!) By contrast, what is already present in a student's mind can significantly impact what can be learned from new information.

Framed in the context of education, this is eloquently put by philosopher Ernst von Glasersfeld (1989):

> *"Verbally explaining a problem does not lead to understanding, unless the concepts the listener has associated with the linguistic components of the explanation are compatible with those the explainer has in mind. Hence it is essential that the teacher have an adequate model of the conceptual network within which the student assimilates what he or she is being told. Without such a model as basis, teaching is likely to remain a hit-or-miss affair. From the constructivist perspective, 'learning' is the product of self-organization"*

Teaching by Telling is Ineffective

As stated in McDermott (2001), teaching by simply telling students how things work and what traps to avoid doesn't work for most students. The generalization is based on extensive research within the University of Washington Physics Education Group. Thus, any impact that I might hope to have on the specific topic of teaching longitudinal standing waves must be carefully considered against this statement. For this reason, some form of interactive engagement must take place in order to improve upon traditional, lecture-based instruction. A few examples of such interactive engagement methods are *Tutorials in Introductory Physics* (McDermott and Shaffer, 2002), *Interactive Lecture Demonstrations* (Sokoloff and Thornton, 2004), and *Peer Instruction* (Mazur 1997).

Large-scale Knowledge Structures

When attempting to develop an idea of what students are thinking about a particular concept, we can consider whether or not their responses to questions about that concept fit a pattern that describes a robust model. Such a model that students reliably and repeatedly draw upon to make sense of physical situations would be referred to as a concept. If it is an errant model – that is to say one that does not agree with what an expert would choose to describe the same phenomena – it is often referred to as a *misconception* or *alternate conception*. These two terms mean effectively the same thing, and just like correct concepts, they are also triggered reliably and repeatedly. By contrast to smaller-scale knowledge structures, they are much more difficult to change. For

longitudinal standing waves, we will see that such rigid reasoning structures are not common.

Fine-Grained Knowledge Structures

The idea of well-developed, robust misconceptions is at best an incomplete representation of student difficulties in learning physics (as is a model based purely on small scale structures). While students sometimes follow well-developed models, a purely misconception-based view of student learning and understanding fails to consider the "raw materials" that can be used in constructing a more productive understanding. (Hammer and Elby, 2002/2003). In fact, a variety of studies with students find that the naïve reasoning of students is generally not consistent with that of a misconception model (reference – list from Hammer and Elby 2003, p55). A more adequate way to model student learning is to consider what epistemological resources are available for use by the student. These resources are similar to what diSessa (1993) refers to as phenomenological primitives, or "p-prims." In contrast to the developed, robust incorrect model represented by a misconception, a student's understanding is considered to be the product of one or more pieces of reasoning that on its own is neither correct nor incorrect. The situation in which such a p-prim is triggered and applied determines the correctness or incorrectness of the reasoning. For example, an idea that "closer means more" is such a statement that is neither correct nor incorrect until used in context. As your hand approaches a stovetop burner, the closer you get, the hotter it feels. In this case, "closer means more" is triggered properly. However, an inappropriate trigger of the same resource could happen when considering the Doppler shift of a horn on a car approaching

an observer. If the car moves at a constant velocity toward the observer, "closer means more" would trigger the incorrect response that the closer the car gets, the more of a Doppler shift is present.

Of particular interest to concepts of sound is diSessa's p-prim of *guiding*. Under the *guiding* p-prim, the existence of a given path or pattern is sufficient to explain that an object will follow that path. For example, the motion of a ball rolling inside a curved tube requires no explanation if the student activates this p-prim – the ball just naturally follows the curve of the tube. The student does not feel compelled to add to this description as it seems complete.

Another example of the incompleteness of misconceptions model of student understanding is that it places an expectation that there are stable, robust, counter-productive misconceptions that can be elicited and confronted. For concepts in which students have regular day-to-day experience (force causing motion vs. force causing acceleration, for example), this approach applies well. For concepts in which students have little to no exposure (longitudinal standing waves, for example), this approach is not well suited to describe student difficulties, simply because student ideas are much more fragmented and often fail to develop into a true misconception.

Triggering such epistemological resources can be thought of as getting the student in the right frame of mind to understand a difficult concept. Often students listen to the description of a topic in lecture that seems quite understandable. However, when the student tries to solve problems or consider situations involving that topic, they may be at a loss for a starting point. In some cases, they are aware that a certain concept applies,

but have little idea how to proceed. In others, the idea that a certain concept would apply is never triggered. These cases seem too different from what they have heard about in class, and as a result no progress can be made. When a concept and a situation in which it applies are of this sort, the use of bridging analogies (Clement, 1993) can help to "bridge the gap" between the two situations, making the student more aware of the relation between the two seemingly unrelated situations. Clement's classic example is the nature of the normal force exerted on an object by the object on which it rests. In this case, an object is placed on a trampoline and on a table. Students readily accept that the trampoline exerts an upward force on the object, but many students do not respond the same way about the object on the table. Often, the table is considered to just be "in the way" keeping the block from falling. The bridge between these two concepts is a wooden board supported at its ends while books are placed on top. At first, the board is straight, but bends as more books are added. The bending makes it easier to see that an object that doesn't appear "springy" like a trampoline still does exert an upward force.

Epistemological resources are slightly more general ideas which help the student to consider how knowledge is constructed, or how it is the student knows what he or she claims to know. Even at young ages, children have a sense of the difference between *knowledge as inferred* ("I know because you told me") and *knowledge as invented* ("I know because I made it up"). (Hammer and Elby, 2003) The latter is referred to as "free creation", where the knowledge has no other source than the person who generates it. This is in contrast to *knowledge as fabricated stuff* ("I know because I figured it out"), in which one could expect that others with access to the same information could also learn

what the first person figured out. In using the knowledge as invention resource, another student has no way of reconstructing the knowledge generated by the first.

Students draw upon epistemological resources when learning anything, including physics, and such resources are not necessarily well-developed in every student. However, curriculum developers and researchers often take for granted that students do have a well-developed set of epistemological resources, and we teach and write curriculum to use those resources.

Prior Work in Student Understanding of Sound and Standing Waves

There is a small but growing amount of literature regarding the student understanding of sound and standing waves. Some mention is made of the difficulty in teaching sound concepts such as sound propagation (Hults, 1980) and pitch, timbre, and loudness (Merino, 1998). Merino's work in particular deals with psychoacoustics – how sound is perceived by the listener. This is certainly an area rich with interesting results, but goes beyond the treatment of sound in this thesis. To borrow an analogy from Menchen (2005), starting a treatment of sound by how it is perceived in the brain is akin to studying how students learn about light by first describing the intricacies of how the eye perceives light.

Eshach (2006) has studied concepts of sound at the middle-school level, finding that students' ideas of sound are heavily substance-based, and often internally inconsistent. It is a theme that persists in investigations of student understanding of

sound at collegiate levels. Fazio et. al. (2008) have also experimented with a teaching and learning sequence with high-school students.

In the specific context of physics education research at the collegiate level, some relevant work has been done in the arena of mechanical waves and sound propagation, which I will focus on in detail below. While they do not specifically address the topic of longitudinal standing waves, they articulate some of the basic concepts that students use to describe their own understanding of wave phenomena.

Mechanical Waves

Wittmann identifies two critical concepts that students need to learn to understand "ideal" small-amplitude wave phenomena. First, "wave propagation is a medium's response to a disturbance." In other words, how a wave will propagate through a medium depends only on that medium, not on the nature of what caused the wave. Second, "wave superposition occurs by adding individual displacements point by point at any given time." I will focus on the first concept, which is the one that relates most directly to this thesis.

Wittman probed this first concept with students in the second semester of a three-semester university physics course. A string was attached to a wall at one end and held taut by a hand at the other. The hand had created a pulse on the string, and after a time t_o it reached the wall. Students were asked (in interviews, free-response questions, and multiple-choice questions) how they would decrease the time it would take for the pulse to reach the wall. If there were multiple ways to do so, students were asked to identify them. Seventy-three percent of the students (N=92) answering a free-response question

identified only the motion of the hand (by moving the hand faster, with larger amplitude, or by "putting more [or less] force" into the wave) as the way to change the speed of a pulse on a wave. When presented with a multiple choice version of the same question, almost 90% still included hand motion as a possible answer, though now 73% of the students had identified both hand motion and properties of the medium as ways to change the pulse speed. The students appear to recognize the correct answer when it is presented in the multiple choice question, but the incorrect identification of the hand affecting the wave speed is robust. More than 50% of this class still responded that the hand would affect the pulse speed, even after modified, PER-based instruction. This question was also asked of a class after traditional instruction (N=116, not matched to the other class). More than 70% responded that the hand motion would affect the speed of the wave.

Wittman claims to see evidence for what he calls the *Particle Pulses Mental Model* of waves. Such a model incorrectly uses ideas of force or energy to describe the characteristics of waves and wave motion. One aspect of this model draws an analogy between wave motion and throwing an object, in which throwing harder or with more force results in a faster motion of the object. Another is to consider that a large object moving with a given speed has a given amount of [kinetic] energy. Using the *Particle Pulses Mental Model*, a smaller pulse with the same energy could be reasoned to be moving faster (smaller pulses move faster).

Another example of student difficulties about sound is the confusion between the motion of the longitudinal wave and the motion of the medium. In other words, students often treat a sound wave as an object rather than as an event, putting it into the wrong

coordination class. (Wittmann, 2002) Coordination classes are a model for structuring one's knowledge by associating concepts with similar features with one another. Chi (1992) states that classification errors between closely-related categories are easier to "fix" than errors between more general categories. A particularly troublesome classification error occurs when it occurs at a very general level, such as the distinction between objects and processes. Brown (2005) verifies this in studying the difficulties encountered by university students who have made such a classification error with electrical current.

Wittman (1998) recounts the reasoning of students interviewed about the effect that a tone-producing speaker will have on a dust particle located near the front of the speaker. The very common incorrect response is that the dust particle will move away from the speaker as if carried off by the sound wave. Student interview data support that this is a robust and reasonable way for students to think about sound. A representative view is that the incoming sound wave hits the dust particle over and over again, with each "hill" in the wave giving the dust particle a push. Wittman likens it to a surfer being pushed forward by the leading edge of an ocean wave.

Students also draw from their everyday life experiences (Hammer's resources) in answering such questions. One student mentioned the idea of turning a stereo system to a loud enough level so that he could feel the sound hitting his chest. These repeated hits were then considered to be similar to what the dust particle would feel, causing it to be pushed outward by the action of this repeated outward force. In another example, Wittmann (2002) sees evidence of fragmentary reasoning in terms of diSessa's "Working

Harder" p-prim. A student responded to a question about how to make a wave pulse travel more quickly down a taut string held in one hand and attached to a wall at the other end. "You flick [your hand] harder…you put a greater force in your hand, so it goes faster." The student clearly showed the up and down motion of the hand and wrist slowly to represent how to produce a slow pulse, and quickly to produce a fast pulse. While the student may not have had direct experience with this particular apparatus, he may subconsciously draw upon other experiences where *more effort* generates a *faster motion*, such as throwing a baseball. The student was unable to explain why the hand motion created a faster pulse speed, but just asserted that it was so, and considered that assertion to be sufficient to make sense of the situation.

The dust particle question above also asks about the motion of a candle flame in a similar position. Responses from the interviewees were largely consistent with the above reasoning, stating that the flame would be knocked to the side away from the speaker and held there, or be knocked repeatedly, causing it to oscillate between upright and the "away" position.

Traditional lecture instruction seemed to have minimal impact on students in an engineering physics course. In their responses to the dust particle question above, 14% of the students demonstrated the use of a proper longitudinal wave model before instruction, increasing to just 24% after instruction. (Note that these are unmatched sets of students in successive semesters with N~100 in each case.) This provided motivation for the development of curriculum on longitudinal waves that would address the reasoning often used by students.

In this tutorial-style instruction, students predict the motion of a candle flame near a speaker, then watch digitized video of what happens when the speaker is turned on. The goal is to put the student in a situation where they recognize that object-like properties (like waves hitting objects and pushing them away) are insufficient to describe the wave. The students see the motion of the candle flame clearly moving on both sides of the equilibrium position and must both account for that motion and also resolve any discrepancies with their original prediction.

Later in the tutorial, students create a graph of the displacement of the candle flame versus time to determine the period of this sound wave. This is then linked with the frequency of the wave. This allows students to put their observations together with the standard mathematical and physical descriptions of the wave commonly found in traditional instruction (and homework!).

Students also view a photograph of two candles placed in front of the same speaker at different distances. Based on the orientation of the two flames, the students are asked to draw displacement versus time graphs for each flame. They are also asked to imagine the behavior of a long line of candle flames, and determine the wavelength of the sound wave using that idea.

The effect of this instruction raised student performance on the dust particle question mentioned earlier. The tutorial students (N = 137) answered the question 9% correctly before instruction and 26% correctly after lecture, not drastically different from the non-tutorial students. After tutorial instruction, 45% of the students answered correctly. An additional 20% left the question blank, so the 45% is potentially an

underestimation of student performance. The question was at the end of a longer survey which students had a limited time to complete.

Models of Sound and Sound Propagation

Linder (1989) was one of the first to attempt to identify categories that would represent the way that students at the collegiate level talk and think about sound. He conducted interviews with ten Canadian students with degrees in physics or engineering who were in a one-year preparatory program to become high school teachers. The interviews were conducted as a conversation about a variety of subjects from everyday experiences of sound, simple physics demonstrations, and graphical representations of sound. He found that students chose to use different modes of explanation depending on the context of the question. He cast these modes in terms of two explanatory perspectives, microscopic and macroscopic. The microscopic perspective relied upon the actions of individual molecules or particles of the medium, while the macroscopic perspective dealt with the bulk properties of the medium, such as pressure and density. One of the difficulties students had with the microscopic perspective was the idea that individual molecules in a medium "carry" sound. That is to say that there is a net displacement of particles from the sound source to the listener, and that net movement sends sound to the listener.

This same idea is evidenced by students in terms of the macroscopic perspective by loosely defining sound as a sort of "wind" in which air must travel from the source to the listener to be heard. A variation on this model is a "cowcatcher" model of sound propagation where sound is treated as something that pushes air in front of itself (in the

way that a cowcatcher attached to the front of a train could push a cow if it were to be in front of the train.)

Linder also identified a category of responses in which students vaguely described sound as bounded in some form of "traveling pattern." Upon further questioning, this seemed to be rooted in an assortment of learned physics language and "disembodied facts" that don't give an intuitive sense of what is happening.

Some difficulties with resonance and sound propagation have been also documented by Menchen (2005). Of particular interest are some of the interviews about resonance conducted with pre-service and in-service teachers. Students were asked questions about tuning forks that had been attached to another object and the ability of that object to transmit the sound to another object (from a meter stick to a second tuning fork in one case, and from a string to a plastic cup in another.) While students were able to correctly identify that the sound could be passed through the medium, they often considered this medium as incapable of producing sound itself. Thus, the students were exhibiting a difficulty associating vibration with sound depending on the context of the situation.

Hrepic et. al. (2005) interpret student understanding of sound propagation in terms of four main models. In earlier work (Hrepic, 2002) he identified two "base" models that could characterize student responses using a model analysis technique proposed by Bao (Bao and Redish, 2000). These are the scientifically accepted Wave Model, the main alternative model called the Entity Model. A "no model" state was also used for responses that were inconsistent with the features of those two models. These

three model states can be used to characterize students' ideas about sound propagation. Hrepic later adds two major "hybrid models" described later in this section.

The Wave model describes sound as a longitudinal vibration of the particles of the medium, in which sound propagates as a traveling disturbance of these particles. In the Entity model (also referred to as the Independent Entity model), sound is considered to be its own substance or entity, separate from the medium in which it is present. In this model, sound propagation does not require a medium, although interactions with the medium are possible. Some of the conclusions drawn from such a model are that sound can travel through a vacuum, that sound is a substance or material of its own, that these "sound particles" can propagate, and that sound can travel by "seeping" through empty spaces in a medium.

Hrepic gave a variety of surveys and conducted interviews with students in all levels of college introductory physics courses. His results indicate that students rarely use the Wave or Entity models exclusively. Rather, they use specific parts from both models in regular patterns, even though the parts of the models selected are logically inconsistent. Hrepic attempts to make sense of student responses by imposing his own classification scheme of "hybrid models," which are regularly-used manifestations of parts of the Wave and Entity models. He identifies several hybrid models which he condenses to two main hybrids based on the common features of those models.

The Intrinsic model draws from the wave model by incorporating the need for a medium and excludes the idea of a separate sound substance. It borrows from the entity model by stating that sound propagation happens by a net motion of the medium particles

away from the source. Those particles may or may not be vibrating as they move away. The Dependent Entity model borrows from the wave model by requiring a medium for the propagation of sound. However, it heavily borrows from the Entity model, describing sound as its own entity that propagates by using the motion of the medium and/or the empty space between the particles of the medium. Variations within this hybrid allow for particles of the medium to vibrate in place or have translational movement in the direction of sound propagation.

Hrepic used a six-question multiple-choice survey to describe the model or hybrid model a student used with regard to sound propagation. The questions describe the motions of medium particles and their relation to the sound present. Contexts of the questions are one person speaking directly to another, one person speaking to another through a solid wall, and a person attempting to listen to a ringing bell that is housed inside an evacuated box. By matching up triplets of responses, he categorized student responses into one of the aforementioned models. Among his results, he found that only a small percentage (10-15%, depending on the context) of the post-instruction university students he surveyed consistently used proper wave models to describe sound propagation. Approximately 80% of the students could be classified as using either alternative models or the aforementioned hybrid models.

CHAPTER 3

DEVELOPMENT OF THE STANDING WAVE DIAGNOSTIC TEST

The Genesis of the Project

My teaching experiences in introductory physics classes left me with an impression that students rarely left with a broad understanding of how sound worked. They could apply formulae that described closed and open pipes, but their understanding of the physics behind such phenomena seemed to be lacking.

In the Spring 2004 semester at Montana State University, I had an opportunity to ask an exam question of the students in the algebra-based second-semester physics class, Physics 206. The structure of the class is partially traditional (three 50-minute lectures a week) and partially non-traditional (University of Washington-style tutorial format during a two-hour lab period each week). The Physics 206 students undergo instruction about sound and mechanical wave concepts at the start of the semester – it is not a subject of instruction in their first-semester course (Physics 205). Based on some preliminary work with other classes in the fall semester, I constructed the following question to be put on the Physics 206 first exam:

> *Two pipes are resonating at a frequency of 50 Hz. One has both ends open, and the other has one end closed and one end open. Consider air particles A (in the open-open pipe) and B (in the open-closed pipe). A and B are located halfway between a node and antinode in their respective pipes. With what frequencies are the two air particles oscillating back and forth inside their respective pipes?*
>
> *a. 50 Hz for particle A, 50 Hz for particle B*
> *b. 50 Hz for particle A, 25 Hz for particle B*
> *c. 25 Hz for particle A, 50 Hz for particle B*

d. 25 Hz for particle A, 25 Hz for particle B
e. A frequency can not be assigned to particles A and B

I consider this question to be "complex" in that it involves multiple pieces of reasoning to be used in order to come up with a correct answer. An expert may be able to pick up the necessary information from the first sentence, noting that if the pipe produces a sound at 50 Hz, then the particles of the medium producing that sound must also move with that same frequency. Hence, choice (a) is correct. There are many other considerations, however, that distract from this concept. Among them are the fact that one pipe is open at both ends while the other is only open at one end. Students are commonly taught that there is "a different formula" for closed-open pipes and open-open pipes, which might lead them to select choices (b) or (c). Also, since the particles are said to be halfway between a node and antinode, there is another cue that something should be halved, perhaps directing students to select answer (d). If the student does not see a connection with sound frequency and oscillation frequency, they may be inclined to choose answer (e).

The students in the Physics 206 class (N = 90) selected answers (a) through (d) at the rate of 20 to 25% each, and 10% chose response (e). Despite having had instruction on sound, which included mechanical waves, transverse waves, longitudinal waves, and individual particle motion within a wave, the students fared negligibly better than if they had simply guessed. In fact, the distribution of answers suggests that many of the students were unable to locate a concept that would help them, and likely did end up guessing.

This example shows that a student's understanding of standing waves can be very weak, even if it is addressed in the lecture and in tutorial. It was a genuine surprise that the students had spread their answers so evenly across the response choices. This suggests that the students' conceptual understanding of sound was largely insufficient to make sense of this question. Useful conceptual processes students may have developed in their learning of sound did not appear to have been triggered in this situation.

Exploring Student Difficulties: Preliminary Introductory Physics Surveys

In an effort to identify some of the difficulties students had in understanding sound and standing waves, a variety of surveys were given to students in introductory physics classes at Montana State University. The primary goal of these surveys was to identify the types of conceptual difficulties that students had. Some of these difficulties are described below.

Physics 211, Fall 2003

The first of these was given in the Fall 2003 semester to students in Physics 211, a first-semester calculus-based physics class. At the time of this survey, the students had started but not yet completed lectures covering sound and waves. The goal of this initial survey was to identify a variety of student difficulties on the topic of sound and standing waves. Students were given 5- to 6-question surveys with multiple parts per question during the first 15-20 minutes of their lecture class. Some of the more interesting difficulties students encountered are illustrated below.

A pair of questions (Question 1 and 2, Appendices A-1 and A-2) on each survey probed the students' understanding of the direction of motion of individual air particles within a resonant pipe. Students were given a typical textbook picture of a longitudinal standing wave in a closed-open pipe, showing both the pipe as well as a double sine curve representation of the standing wave inside. A single curve would be correctly interpreted as a plot of the maximum displacement of an air molecule away from its equilibrium position versus its position along the length of the tube. Thus, the "double curve" represents the range of longitudinal motion for an air molecule given its longitudinal position within the pipe. Assuming that we ignore random thermal effects and simplify the situation to that of a pure longitudinal standing wave, all motion (if any; particles at nodes wouldn't move) should be along the length of the pipe.

This hybrid representation of a longitudinal standing wave – a graphical representation of a standing wave superimposed on a physical picture of the tube – leads to difficulty interpreting the meaning of the curve. However, students commonly selected non-horizontal directions for the motions of some of the particles. In fact, only about 1 in 5 students gave responses that did not involve any vertical or diagonal motion.

In addition, students were asked to explain what was useful about the picture in selecting their answer. The most common response was that they looked at the picture to determine locations of nodes and antinodes, which helped them to choose their arrows accordingly. Others stated that they were guessing or had not specifically covered this information yet. It seemed reasonable to assume that students often did not know how to

interpret the picture, and those that did used it primarily to mark nodes and antinodes of displacement.

The difficulty in expressing the meaning of the hybrid representation was also evident in another question from a different survey asking students to sketch standing waves in a pipe and to explain what the lines in their sketches represented. Nearly every student drew sinusoidal curves within the pipe consistent with a hybrid model representation of a standing wave in a pipe. Responding to the prompt for explanation, students often gave generic responses stating that the curve "was the wave" or represented the sound wave.

A second pair of questions (Questions 3 and 4, Appendix A-1) probed the understanding of pressure nodes and antinodes, a topic that had been discussed in class. Students were presented with the same picture as in the first pair of questions and asked to identify which of four points listed (two at pressure nodes, two at pressure antinodes) were places where the pressure was changing. The students for the most part were able to answer this question correctly, often indicating that places of no motion were the places of greatest pressure change. Others stated that there were two pressure antinodes, supporting their statement by inferring that nodes and antinodes alternate along the pipe, so if there were four node or antinode points, two must be antinodes and the other two must be nodes.

The second question in this pair revealed that what the students had learned was more of a memory of patterns than a deep understanding of how pressure works in a longitudinal standing wave. Students were asked in multiple-choice format to identify

the average pressure at each of the four points (pressure nodes and antinodes) in the prior question. In places where the standing wave is causing the pressure to change, the pressure goes both above and below atmospheric pressure, so the average for all points within the pipe is atmospheric pressure. Given the choices of atmospheric pressure, above, below, or zero, virtually all the students indicated that at least some of the points were at a higher or lower average pressure than atmospheric pressure. A common response to the question was for students to state that the pressure antinodes were places of higher average pressure, while nodes stayed at atmospheric pressure or averaged below atmospheric pressure. It is difficult to know from this question alone if the students had difficulty with the actual pressure profile or if they were thrown off by the idea of an average. One way to understand these choices is to consider that the students may be considering, consciously or subconsciously, that pressure nodes were places where the pressure changes, but the change is defined by the pressure going up and staying there, or by going up and then back to atmospheric pressure. The ideas of static pressure profiles as well as the "one-way" oscillation from equilibrium pressure to high and back to equilibrium are pieces that would eventually become part of the Standing Wave Diagnostic Test.

Students were also given an open-ended question asking them to describe the process of sound propagation from the resonant pipe to the listener's ear. The responses generally described disturbances of air particles causing sound. The responses often stopped there, saying the sound was due to "vibration" or "disturbance" of the air molecules. Others described the propagation of sound as pressure variations, the

traveling of air molecules, or the traveling of a sound wave. The incompleteness of responses is not unexpected; it is consistent with similar work done by Hrepic (Hrepic 2002), though they do indicate that sound and sound propagation can very quickly become a black box of sorts, the working of which students have little understanding beyond very basic concepts.

Physics 206 and 211, Spring 2004

Following the initial responses from the Fall 2003 surveys, new sets of surveys were given to students in Physics 211 and Physics 206. In Physics 206, sound and mechanical waves are covered early in the semester. The description of pressure in a resonant pipe was mentioned but not covered at much length in the Physics 206 class. The surveys were given as pre-instruction surveys to the Physics 211 students. Students in the Physics 206 class completed two slightly different surveys, one pre-instruction and one post-instruction. Students were again asked to answer questions regarding the direction of air molecules at given locations within a resonating pipe, pressure, amplitude of motion, and speed of movement. In addition, students were asked to rate their confidence on each question on a scale from 1 (guessing) to 5 (very confident). These surveys are listed in Appendix A-3.

One of the thoughts I had at the beginning of this project was that students tend to have very loosely-constructed ideas about the phenomena of longitudinal standing waves in pipes. Indications of this included what I perceived to be a low level of commitment to their ideas, whether they were correct or incorrect, and answering questions in ways that were not consistent with any single model of standing waves. Responses to the Physics

206 survey were given confidence ratings of mostly 1 or 2 on every question by the students, indicating that the students felt they were either guessing or doing a little better than guessing for each question. Pre-instruction surveys in Physics 211 showed a similar trend – it was rare for students to express confidence in their responses above a slightly-better-than-guessing confidence level.

One of the student difficulties highlighted in the survey was with identifying the direction of motion of air particles in a resonant pipe. Of the 92 surveys given to the Physics 206 students, only 8 responded in a way that excluded vertical or diagonal (non-longitudinal) motion as a possibility. The remainder chose vertical or diagonal directions of motion for one or more of the particles inside the pipe. A similar percentage of students in the Physics 211 class responded accordingly during their pre-instruction survey. This was also evident after instruction in the Physics 211 class. At the end of the semester, students in the class were given six questions relating to longitudinal standing waves as part of a 50-question class final. One such question asked for the direction of motion of a given air particle, with the vibrational mode and motion of one of the other particles already known. Less than 30% (59 of 205) were able to correctly indicate the correct horizontal direction of motion, and more than half (109 of 205) responded with a non-longitudinal direction of motion. This was also evident in a smaller set of post-instruction surveys used with the Physics 206 class.

The surveys (and subsequent exam questions in Physics 211) also indicated other difficulties with students' understanding how pressure is related to longitudinal standing waves in pipes. Given a "hybrid" picture of a standing wave pattern in a pipe, students

were asked to indicate the nature of the pressure (constant or changing, as well as its relation to atmospheric pressure) at locations corresponding to nodes and antinodes of displacement. At displacement nodes, the pressure varies as air particles rush from both sides inward toward that node, and outward in both directions away from it. Conversely, at displacement antinodes, the pressure remains constant as air particles slosh back and forth without compression. The Physics 211 pre-instruction survey showed that students answered with success rates no better than 25% (N = 160), dropping to as low as 4% for certain locations within the tube. In addition, we can consider the responses to these questions in terms of just two options: a changing or a constant pressure. Under that lens, students still performed poorly, with correct response rates from 31-54% at the various locations in the pipe. Results for the identical question on the Physics 206 post-instruction survey were also poor under that lens, with correct response rates of 33-36% (N=72) for the same locations.

Speed of motion was also an issue (Question 2 in Appendices A-3, A-4, and A-5). Students were asked to determine which particle was moving faster while a pipe closed at one end was resonating. The two particles chosen were at a displacement antinode and halfway between a node and antinode, along the central axis of the pipe. After instruction, only 47% of Physics 206 students surveyed (35 out of 74) correctly indicated that the particle at the antinode would in fact move faster than the particle halfway between the node and the antinode. The Physics 211 students had similar results. The explanations offered by students in both classes were generally incomplete. Students who did choose the correct particle frequently offered no explanation. Those who did

attempt to explain their answer often vaguely related the particle's position to the curve drawn inside the pipe. Some of the student responses were:

- *"[particle] i would be moving faster because it is closer to the node"*
- *"[particle] i is faster because it is closer to the resonance"*
- *"[particle] i is moving faster because it is closer to the path of the motion, so there is more force behind it."*

Students had a much better grasp on understanding the amplitudes of the particles in the tube (Question 4, Appendices A-4 and A-5). As an example, when asked to compare which of two particles moves farther (with a greater amplitude), the Physics 206 students after instruction (N = 74) answered correctly over 80% of the time. This seems to be a topic that does not harbor the same difficulties for students as those previously mentioned. I suggest that the reason for this is that the transverse standing wave model is typically the first standing wave model presented to students in a formal way. It can be used to answer the question of amplitude difference, and a correct answer will come out of that model.

Exploring Student Difficulties: Examination Questions

In an effort to get a sense of whether student difficulties with sound extended to a larger population of students, I took the opportunity to place six questions about sound and standing waves on the final exam for the calculus-based Physics 211 class at the end of the 2004 Spring semester (N = 205). These questions can be found in Appendix B.

The only question that a majority of the students answered correctly was the first question, dealing with the speeds of two individual points on a vibrating string exhibiting a transverse standing wave. Seventy-six percent of the students correctly identified that the portion of the string closer to the displacement antinode will move faster in that transverse wave. This suggests that students are able to make some link between the particles of the medium and the overall standing wave for transverse waves.

The rest of the questions involve longitudinal standing waves in pipes. Although not explicitly stated in the problem statements, we expected students to focus on the oscillatory motion of air in the pipe, while ignoring random thermal motion of individual particles. For each of these questions, only a minority of students gave correct responses.

Questions 2 and 3 are problems that require students to draw upon multiple ideas in order to answer correctly. In Question 2, students are asked to determine where in a resonating pipe an air molecule will move the fastest. Rather than describe the points as nodes and antinodes, a double sine curve representation of the standing wave present and the location of the air molecule's initial position are given to students. Students must then recognize that the particle will move longitudinally along the pipe in an oscillatory manner. Students must also recognize that the range of the oscillatory motion of an individual particle is small. The particle does not travel from node to node or beyond, but oscillates around its original position.

Table 1. Summary of results from Spring 2004 Physics 211 exam questions, post-instruction. Correct responses are in **bold**.

Question:	1	2	3	4	5	6
Response						
a	13	12	**36**	25	2	**33**
b	**76**	12	27	17	29	45
c	2	17	14	10	**40**	22
d	9	15	10	2	21	
e		**43**	13	**29**	3	
f				18	4	
% correct	**76**	**43**	**36**	**29**	**40**	**33**

Question 3 is the same question referenced at the start of this chapter, with the difference that the students in this group were taking the calculus-based course. We see that the idea of particles oscillating with the same frequency as the sound emitted from the pipe in which they reside is still difficult for most students; it is not just a difficulty that arises in the algebra-based physics class.

Question 4 addresses the issue of individual air molecule movement when shown in the "hybrid" representation of the standing wave in a pipe. Fewer than half (47%) of the students correctly indicated that the motion would be horizontal, while 42% indicated that the motion would follow the curve superimposed onto the picture of the pipe. This suggests that students often do not have an appropriate interpretation of this hybrid representation.

Question 5 addresses the direction and range of motion of an individual air molecule inside a pipe while the pipe is resonating. The location of the air molecule is chosen such that the "along the curve" distractor, shown to be important in Question 4, does not play a role in Question 5. Students are only given choices that are either longitudinal motions along the length of the tube or transverse motions perpendicular to

the length of the tube. 76% of the students correctly chose a longitudinal motion. However, only 40% chose the correct, small-amplitude oscillation. While it appears there may be some longitudinal motion component in the students' models of standing waves in the pipe, that model may not necessarily include an understanding of how all the particles move and interact to set up the standing wave.

Finally, Question 6 deals with a relationship between pressure and particle spacing, as well as addressing the variation of pressure with time at displacement nodes. In talking with students, I had gotten the impression that one of the student difficulties with pressure in a standing wave was that students often thought of the pressure differences within a resonant pipe to be static phenomena. In other words, while the pipe is resonating, there are regions of constant high pressure and constant low pressure. Students in this case seemed to exhibit that difficulty, as only 33% of them answered correctly that the pressure was unchanged when the indicated particles had returned to their original positions. With only three responses from which to choose, this means that the students fared about as well as they would have if they had simply guessed. 45% said that displacement nodes (where the curves cross) are higher pressure areas, and the corresponding antinodes were at a lower pressure.

Student Interviews

When attempting to determine what students are thinking and what alternate conceptions or misconceptions they may hold, it is generally not enough to solicit responses to written surveys. Even if the questions are written in an open-response

format (i.e. “explain your reasoning…” or “describe…” questions), it is possible that what the student is truly thinking is not the same as what the researcher interprets from their responses. In addition, it is possible that the researcher has overlooked an important alternate conception. This is particularly important with regard to multiple-choice questions. For any multiple choice question to give a good representation of what students think, it should include all the common distractors that students would naturally tend to choose. For example, consider a question about the force exerted on a book by a table on which it rests. A common incorrect response to this question is that the table exerts no force on the book – it is merely “in the way”. A multiple choice question that leaves out this choice forces students into choosing a different answer that may not match their reasoning particularly well. The results of such a question may not accurately represent what difficulties – and to what extent – that students have with that particular concept.

I conducted interviews with fourteen students from the Spring 2004 Physics 206 class for the purposes of confirming some of the issues that seemed to be appearing in the student reasoning from the written surveys. Interviews were conducted from the last week of the semester through finals week after all instruction on sound had taken place. Student participation was voluntary; the students were told that the interviews were being conducted to assist with this project, but neither financial nor course-credit incentives were given to the students. The cross-section of this self-selected group tended to be the students whose grades were in the top half of the class. Thus, any alternative conceptions demonstrated by these students would be likely to be present in the overall class, and

their difficulties could not be simply explained away by claiming that they were weaker students who just "didn't get it." Each of the students had, earlier in the semester, written and submitted the preliminary surveys described above.

Because these interviews were exploratory in nature, I did not restrict the interviews to follow a rigid script. Instead, the interviews focused primarily on the types of questions given in the preliminary surveys, and if a particular difficulty arose I asked follow-up questions to probe the difficulty. I wanted to focus on understanding each student's reasoning about individual particle motion within a standing wave as well as learn about how they understood typical textbook representations of waves.

One of the issues I wished to address in the interviews was whether or not students who chose non-longitudinal directions of motion for air molecules within the pipe really meant what they had written. Some of the students interviewed were comfortable with the idea of purely longitudinal motion of individual air molecules in a resonant pipe, while others were not. I asked one of the students I interviewed to draw a few of the air molecules inside the pipe and describe how they were moving. A "footballs" representation of the standing wave had already been drawn within the pipe. The student described the motion of a particle that had been drawn on the curve inside the pipe as follows:

> *…It just seems to me that this one [indicating a particle on the curve] would be easier to follow this path [indicating movement along the curve], and this one [indicating a particle below the curve near the bottom of the pipe] like it's almost stuck in there for a little bit, but I know it's gotta be, (unintelligible) just push straight out, (unintelligible) follow the curve.*

The tendency of this student is to match up the motion of the air molecule with the presence of an existing curve or pathway. This is a good example of diSessa's p-prim of *guiding*, where the motion of a particle is determined by a curve or pathway, with no further explanation needed for this motion to be justified in the student's mind. When it is more difficult to associate the particle with the curve providing the guiding, the student has difficulty indicating a direction of motion.

Students also expressed difficulty with determining the direction of motion of air molecules inside the pipe but outside the footballs in the wave representation. To probe whether or not my impressions that students have difficulty understanding the hybrid representation of standing waves in a pipe, I asked each of the 14 students I interviewed to draw a standing wave for the pipe that was open at both ends. I had drawn the pipe on the paper and then handed the pencil to the interview student. I took great care in this case to state, "draw a standing wave for this pipe" rather than "draw a standing wave *in* this pipe." Yet when given that direction, each of the 14 students sketched a double-sine curve representation. I also refer to this as the "footballs" representation due to its similarity in appearance to a row of American footballs placed tip to tip.

In addition, each student drew the representation so that it fit inside the pipe. This is not surprising, as it is a typical representation used in textbooks (e.g. Giancoli, 2005) and is one they had seen multiple times during their instruction and on prior surveys. After asking some questions about what the air was doing in the pipe, I then asked the students to consider a sketch similar to what they had drawn but with the curves drawn outside the pipe as shown in Figure 1. This representation has been used in textbooks

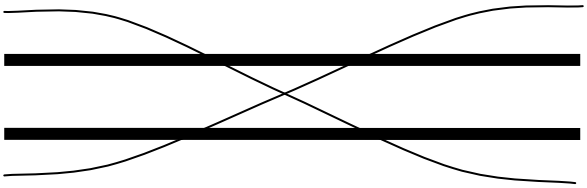

Fig. 1. Hybrid picture of a standing wave in a pipe

(e.g. Knight, 2003) in an effort to discourage students from thinking about the curves as pathways or guides for the air molecules inside the pipe. When I asked the students if this picture made any sense to them, virtually all of them said no because it was implying air motion outside the pipe. One student responded:

> *"It just seems wrong because it…the air's going out along the pipe and then it just somehow comes into the pipe…I don't see how it gets out without going all the way through the pipe first and then coming back out. That just doesn't make much sense."*

Another student suggested that it might make some sense because the air on the outside of the pipe can also be vibrating with what's inside the pipe. In each of these statements, the students are attempting to assign an inappropriate meaning to these curves by implying air motion at the location of the curves. This matches up with the difficulties that students exhibited on initial surveys with the direction of motion of air molecules inside a resonant pipe.

The Standing Wave Diagnostic Test

To better quantify the level of introductory students' ideas about sound and longitudinal standing waves, I created the Standing Wave Diagnostic Test (SWDT) to probe student understanding of such phenomena. The SWDT is a twenty-two question multiple-choice instrument designed to assess students' understanding of longitudinal

standing waves. Questions on the SWDT are all in the context of sound waves in pipes. With the guidance of the initial surveys and interview data, I selected questions that probed student concepts of sound and longitudinal standing waves primarily in three main areas: individual particle motion; pressure variation at individual points and throughout the pipe; and conditions needed for resonance. The SWDT can be seen in its entirety in Appendix C.

The instrument was developed through an iterative process, changing questions as needed if they were found to be misleading or could be interpreted differently. Early versions of what would eventually become the SWDT were used with students in algebra- and calculus-based introductory physics courses at Montana State University. Some questions were found to be incomplete, missing a distracter that students in interviews preferred as a response to certain questions. In such cases, the questions, distracters, or both were edited accordingly. A few questions were eliminated entirely, particularly when students were giving the correct answer for the wrong reasons, or vice versa.

The final versions of the SWDT were used with students in introductory algebra-based and calculus-based physics courses at Montana State University, Minnesota State University – Mankato, and the University of Northern Iowa. The diagnostic was given to students in classroom settings. At Montana State, the diagnostics were administered during two-hour laboratory or tutorial sessions for convenience. Students were given twenty minutes to complete the diagnostic, which generally turned out to be more than enough time for most of the students.

Topics Addressed

The 22 questions on the SWDT are intended to probe some of the problems students have when learning about longitudinal standing waves and waves in pipes. Questions 1-5 deal with student understanding of the direction of motion of individual air particles within a pipe. The students interviewed had little difficulty describing the direction of motion of a point on a string when a transverse standing wave was present. However, the same could not be said when trying to describe the direction of motion of air particles inside a resonating pipe. The picture of paired amplitude curves (or "footballs", due to their resemblance to an American football) inside the tube were often misinterpreted by students, indicating that air particle motion is either perpendicular to the length of the tube or along the curve drawn inside the pipe.

Questions 6, 7, 9, 10, 13, 16, and 21-22 focus on the composite motion of the air particles within a pipe. These questions ask about either the motion of one particle given the motion of another at that moment, or ask for the speed or amplitude of motion of individual particles. Questions 8, 11, 12, and 17-19 address the pressure profile of a resonating tube. Pressure tends to be a very difficult subject for students in the context of sound and standing waves. Instructors frequently skip teaching about pressure in this context in introductory physics courses due to time constraints. In particular, students have difficulty with identifying locations where the pressure should be high or low, and have serious difficulties understanding that the pressure within the pipe is constantly changing. The remaining questions (14, 15, and 20) deal with conditions for resonance in

a longitudinal standing wave in a pipe. Results from pre-instruction surveys with the SWDT are described in the next chapter.

CHAPTER 4

STANDING WAVE DIAGNOSTIC TEST: ADMINISTRATION AND RESULTS

To assess students' ideas about longitudinal standing waves, the SWDT was administered to students in the Physics 206 classes at Montana State University during the Spring 2006 and Fall 2006 semesters. Also, a nearly-final version of the SWDT was used with the Fall 2005 Physics 206 class. The diagnostic used with the Fall 2005 students differs from the current SWDT by exactly two questions in the middle of the test, so I will refer to the results from that set of students only sparingly. Additional surveys not included in this analysis include surveys with students in an equivalent algebra-based physics class at Minnesota State University – Mankato, and with a small set of third-semester calculus-based physics students at the University of Northern Iowa.

Pre-instruction surveys were conducted at the beginning of the semester before the students had instruction on sound and longitudinal standing waves. Students worked through the diagnostics during the first 20 minutes of the class's two-hour tutorial period, though that amount of time was often more than enough for most of the students. Pre-instruction surveys were available for compilation from the Fall 2005 and Spring 2006 semesters. Similarly, post-instruction surveys were conducted approximately one month later in each of the three semesters. Students in the Spring 2006 class received an alternate form of instruction (described in Chapter 5) and results from their post-instruction surveys will be reviewed in Chapter 6.

Interpretations of the Data

Overall Score on the SWDT

The performance of the class on the SWDT can be judged by considering the overall score on the diagnostic. Thus, a first understanding of how well students understand longitudinal wave concepts in the context of waves in pipes can be gained by considering the total score out of 22 possible correct.

The average score of the Spring 2006 Physics 206 class (N = 176) was 7.40 out of 22, or 34%. Ideally, we would like to verify that this is a fair representation of the general Physics 206 population, and not an oddity that is high or low compared to students in other semesters.

The other available pre-test score comes from the Fall 2005 semester students (N = 90). As mentioned at the start of this chapter, the form of the diagnostic was different by two questions. If we eliminate those questions from both the Spring 2006 and Fall 2005 semester data, we now have overall scores of 6.46 out of 20 for the Fall 2005 class (32%) and 6.78 out of 20 (34%) for the Spring 2006 class. While this 20-item abbreviated score is not the exact SWDT, it allows us to make a rough comparison between student populations in different semesters. What we note is that the student performance does not vary dramatically between the two semesters.

Table 2. Physics 206 pre-instruction overall scores on an abbreviated SWDT.

	Fall 2005, pre-instruction	Spring 2006, pre-instruction
Number of students	90	176
Score (out of 20)	6.46	6.78
Percentage	32%	34%

Thus, we have some confidence that we can use our pre-instruction SWDT scores as a baseline by which we can measure the effect of instruction. It is worth noting that there is significant progress that can be made from the initial result of 34% on the full SWDT by the Spring 2006 class. If we use this 34% as a baseline against our post-instruction data, we can determine how much the method of instruction impacts the learning of the longitudinal standing wave concepts.

It is not quite appropriate to call the method of instruction used in Physics 206 in the fall semesters "traditional." The course involves three lectures per week which are fairly traditional in format but informed by the methods and results of physics education research. The instructors of the Physics 206 classes involved in this study are aware of a broad range of common student difficulties with physics concepts, including sound. They construct their lectures in ways that attempt to address these issues. But despite these accommodations, the periods are still lectures. Consequently, they remain somewhat traditional. However, students also participate in a two-hour tutorial session each week, which is a significant and effective departure from traditional lecture. While it is common in physics education research literature to distinguish between groups receiving "traditional" and "non-traditional" instruction, that distinction does not represent the difference well in this case. Instead, I will refer to the students in Physics

206 classes receiving alternate instruction using the Longitudinal Standing Waves Tutorial (described in Chapter 5) as "treatment" groups. Students in the standard Physics 206 classes receiving no change in instruction will be referred to as "non-treatment" groups.

The non-treatment group in the Fall 2006 Physics 206 class improved upon the baseline score for the pre-instruction SWDT, obtaining a score of 11.34 out of 22, or 52%. This is a gain of 3.96 points and an improvement of 18% above the pre-instruction baseline. But the more useful statistic to use is the measure of normalized gain (Hake, 1998) to describe the increase in performance. Simply stated, the normalized gain <G> is the fraction of the total possible improvement that the class could have obtained, given their initial pretest scores. Consequently, the maximum possible normalized gain in each situation is <G> = 1. Specifically, what is reported here is referred to as "average normalized gain" because it is calculated using the aggregate class pre-test and post-test scores, rather than combining individual student normalized gains. For the Fall 2006 class, the baseline score is 7.40, leaving the group with the potential to improve their score by 14.6 points to the maximum of 22. The actual amount of gain in the SWDT score is 3.96. Therefore the normalized gain <G> is the ratio or 3.96/14.6, or 0.27.

Table 3. Fall 2006 Physics 206 post-instruction scores.

	Baseline: Spring 2006, pre-instruction	Fall 2006, post-instruction
Number of students	176	128
Score (out of 22)	7.40	11.34
Percentage	34%	52%
Gain		3.96
Normalized Gain <G>		0.27

Hake describes normalized gains in terms of low (<G> under 0.3), medium (<G> between 0.3 and 0.7), and high gain (<G> above 0.7) domains. Using the Force Concept Inventory as his diagnostic test, Hake found low gains to be a common characteristic of lecture-based instruction. The non-treatment group's performance after instruction on the SWDT also demonstrates a situation of low gain, though it is near the borderline between low and medium gain. This is not entirely unexpected. While the Fall 2006 Physics 206 class includes non-traditional methods of instruction (tutorials) for some topics, no such tutorial is used for the longitudinal standing wave subject matter. Thus it is reasonable to expect that the Fall 2006 students performance on the SWDT would fall into the low gain category, as most of their instruction on longitudinal standing waves would have come from lecture.

Individual Question Performance - Examples

In an attempt to learn more about what students seem to understand and what they have difficulties with, we can look at the performance of the students on individual questions on the diagnostic. It is important not to read too much into the information derived from student performance on a single question. Factors such as the context or the representation chosen for the problem may be contributing factors to the level of performance by the student. But that said, we are always interested in those questions that an expert can understand readily while at the same time seeming to give novices trouble. In particular, it is interesting to look at those questions that give students trouble despite having had instruction on the subject.

Table 4. Fall 2006 Physics 206 scores on individual questions, post-instruction. (N = 128)

Question	Correct response	% correct
1	A	64
2	D	83
3	A	69
4	A	65
5	A	66
6	A	45
7	B	87
8	D	40
9	A	38
10	B	58
11	B	61
12	B	13
13	B	45
14	D	46
15	C	48
16	E	17
17	C	31
18	B	26
19	A	38
20	A	41
21	A	74
22	C	80

Table 4 shows the raw data for the Fall 2006 Physics 206 student group, post-instruction. Some questions do not pose problems for many students after non-treatment instruction. However, there is room for improvement on most questions, and a few of the questions indicate major student difficulties. The most difficult questions based on percentage of correct responses were questions 12, 16, 17, and 18.

Table 5. Fall 2006 Physics 206 post-instruction responses to SWDT Questions 12, 16, 17, 18. (N = 128)

Question	Response (%)					Other/ No response (%)	Correct response	% correct
	a	b	c	d	e			
12	38	13	34	14	-	1	b	13
16	10	10	22	41	17	0	e	17
17	10	16	31	41	-	3	c	31
18	12	26	16	45	-	2	b	26

Questions 12 and 17 both deal with the time-dependent nature of the pressure profile within a resonating pipe. In question 12, air molecules at two locations are identified, one at a displacement antinode (and hence pressure node) at the open end of a pipe, and one at a displacement node (pressure antinode) at the center of an open-open pipe. The student is asked to determine at which of those two points the pressure will be changing. The pressure only changes at **b**, the pressure antinode. Yet 72% of students respond with answers **a** and **c** which demand that the air molecule at the end of the tube experiences changes in pressure. The open end of the double-sine curve at the end of the pipe perhaps suggests to the students that *something* is changing, That fragment of reasoning may trigger the student to respond in a way that suggests the pressure is changing at the open end of the pipe.

Question 17 asks about the pressure at the closed end of a pipe during resonance. Given that the pressure is measured to be exactly 1 atmosphere at one point in time, students are asked to predict the possible values for the pressure at that point. The pressure at a pressure antinode, such as the one at the closed end of a pipe, varies above and below the median value (1 atm), so **c** is the correct answer. However, 45% of the students select answer **d**, that the pressure is constant. This seems to expose the difficulty

that students consider the pressure profile to be a static phenomena while the pipe is resonating – that some locations within the pipe can exhibit higher or lower pressures, but those values don't vary during the resonance.

Questions 16 and 18 deal with slightly different aspects of individual particle motion within the pipe. In question 16, the critical issue to understand is that air molecules in a resonant pipe exhibit a back-and-forth oscillatory motion, and that they move the fastest when they return to their equilibrium position (at which point they continue past it to the other end of the oscillation.) The largest percentage of students (41%) incorrectly select answer **d**, that the particle speed is the greatest halfway between the equilibrium and maximum displacement positions. This is suggestive of an error that showed up in interview data, where students would represent the motion of air molecules within a "football" in a pipe by dividing it in half, allowing air molecules on the left half to move to the left while the air molecules in the right half moved to the right. Without realizing it, they are creating a displacement node in the middle of the "football."

Question 18 asks about the nature of particle motion in a resonating pipe, specifically about how the frequency and amplitude of motion of air molecules differs along the length of the pipe. All the particles participating in the motion to produce the standing wave must oscillate at the same frequency, regardless of their position within the tube. However, the amplitudes can be very different. The most common incorrect answer (45%) was that neither of these quantities change, implying a lack of understanding of the overall motion of the medium.

Each of these issues is addressed in direct or indirect ways in the Longitudinal Standing Waves Tutorial, which is discussed in the next chapter.

CHAPTER 5

LONGITUDINAL STANDING WAVES TUTORIAL DEVELOPMENT

Rationale for Choosing Tutorial-Style Instruction

As described in the previous chapters, students have significant difficulties understanding longitudinal standing waves. Many of those difficulties persist even after traditional instruction. This motivated me to use the approach of a tutorial-style curriculum to help with instruction on longitudinal standing waves. In an effort to address some of these difficulties, I prepared a curriculum roughly patterned in form after the tutorial model of the University of Washington Physics Education Group's *Tutorials for Introductory Physics*.

It is worth recalling from Chapter 2 that teaching by telling is ineffective for most students, especially for difficult conceptual areas in physics. The concept of longitudinal standing waves seems to be one such area. One of the problems is that longitudinal standing waves are often difficult to visualize. For the case of standing waves produced by the air column inside pipes the medium can not even be seen. This is unlike the example of producing a transverse standing wave on a string, where the movement of the medium can be directly observed with a simple demonstration – in short, you can see the "footballs."

In addition, the reasoning used by students to address questions about longitudinal standing waves seems to be very fragmented. Students may apply portions of their reasoning drawn from transverse wave concepts, but tend not to follow a robust,

overarching model. This is not unexpected and aligns with Hrepic's (2002) comments about students' understanding of sound propagation. The approach of traditional, lecture-and-homework instruction commonly makes use of transverse standing wave concepts as the analogy to be followed for longitudinal standing waves. This creates its own problems, and I sought to prepare a different curriculum that did not rely on transverse standing waves as the initial introduction to longitudinal standing waves.

I have had significant experience using the tutorial method of instruction in two-hour tutorial sessions with students in Physics 205/206 classes at Montana State University. I have found these sessions to be very successful in getting students to recognize their own conflicts in reasoning. This is required before effective change can begin, and the tutorials do a good job of effecting that change. By writing a curricular intervention in this format, it allowed me to make use of the existing educational structure in place for the Physics 206 course.

Overview of the Longitudinal Standing Waves Tutorial

The goal of the Longitudinal Standing Waves (LSW) Tutorial (Appendix D) is to get students to think about the physical nature of longitudinal standing waves. This subject is often taught in a way that makes pattern-matching and memorization the primary method of learning for students, leaving the students to recall which of the patterns is appropriate in a given situation. Typical textbook questions often reward this process. In the event that they select and apply the wrong pattern, there is rarely a check to signal that their choice was errant.

The LSW Tutorial is written in the spirit of the Tutorials for Introductory Physics produced by the Physics Education Group at the University of Washington. Students using such tutorials work in groups and discuss situations where there is often a conflict between their understanding of a physics topic and that of an expert. The construction of the tutorial encourages a Socratic dialogue between members of the group, with occasional external guidance from peer instructors in the room. The role of the peer instructor is to help to answer questions by guiding the group's discussion, rather than simply intervening with the correct answer or model. Tutorial-style instruction is most effective when the students truly construct their own understanding and work through their own cognitive conflicts. Though the process can be shortened by having an instructor available to provide or confirm answers, that intervention can cause students to rely on authority for answers instead of developing their own understanding.

Only very simple equipment – a vertical tube with tuning fork and a coiled metal spring (Slinky) – is needed for the tutorial. The tutorial begins with the students marking individual coils on a Slinky and producing a longitudinal standing wave, observing the motion of individual coils in the process and attaching a meaning to the terms "node" and "antinode" in a longitudinal situation. This is followed by discussions of particle motion and pressure within a closed-open pipe, and the introduction of the ideas of pressure nodes and antinodes. Students then demonstrate that resonance doesn't happen in all pipes for a given tuning fork. The tutorial ends with a discussion of the common "hybrid" representation of sine curves inside pipes commonly used to describe standing waves in pipes.

Issues Addressed in the LSW Tutorial

Visualization of Longitudinal Standing Waves

Longitudinal standing waves are difficult to see. Visually, students and professors both have an easy time seeing and describing transverse standing waves. The pattern of consecutive ovals or "footballs" seen in a transverse standing wave is easily produced in a string, spring, or other apparatus, and is easily drawn on paper. By contrast, longitudinal standing waves are difficult to show clearly and are quite difficult to represent on paper. This is one reason why so many texts and instructors use transverse standing wave pictures and patterns to describe longitudinal standing waves. This contributes to the inability of the student to understand the motion of the wave medium in a longitudinal standing wave. Simply ignoring or attempting to shield the student from this representation in favor of another seems unwise, as many students have seen it in prior classes or in a textbook. From interviews conducted with students, it is clear that the representation is a memorable and powerful one, despite its flaws. Because this hybrid representation of longitudinal standing waves in pipes is so common, one main focus of the LSW tutorial is on helping students to correctly interpret this representation. The tutorial thus begins with this issue.

Students are asked to first produce transverse standing waves by shaking a coiled spring back and forth on a tabletop. As they create the standing wave, they watch the motion of some individual coils marked with tape. They identify nodes and antinodes, specifically noting that nodes are points of no motion, while antinodes are points of

maximum motion, both above and below the equilibrium position of the spring. They also note that marked coils that are neither nodes nor antinodes move with smaller amplitudes than those at the antinodes. The tutorial uses these observations as analogies for phenomena in the longitudinal standing wave.

Students are then asked to produce a longitudinal standing wave and make similar observations. Which standing wave they produce is not critical, only that it shows motions that are representative of nodes, antinodes, and intermediate points. Instructors sometimes need to intervene at this point as the production of a longitudinal standing wave is difficult for some students. Trial and error has shown that the longitudinal standing wave is more easily produced by having one person hold both ends of the spring rather than having a different student hold each end.

The flagging of individual coils is a simple but very powerful technique in demonstrating that coils move longitudinally with differing amplitudes. Students quickly identify nodes and antinodes, and address the varying amplitudes of motion in a mock student debate at the end of the first section. The student debate is another technique borrowed from the University of Washington *Tutorials*. In one form of these student debates, students working through the tutorial are presented with two student statements about a phenomenon or situation, and are asked to agree or disagree with them.

Students also commonly enter into a discussion of whether the ends they are holding should be considered nodes or antinodes. Such a discussion is not necessary to complete the tutorial, but is a question they can answer based on their newly visually enhanced definitions for nodes and antinodes. If their hands are moving back and forth

over a significant distance, they could be treated as displacement antinodes, while if they demonstrate little or no motion, they could be viewed as displacement nodes.

Air Column Resonance and Particle Motion

The tutorial continues by addressing the issue of particle motion in a longitudinal standing wave in an air column. A tube and tuning fork matched for resonance are used by the students to create a resonant sound. Students then rely on their prior work in the tutorial to draw connections between the longitudinal standing waves in the spring and in the air column. Without such direction, students (including those interviewed as a part of this work) often are content to say that the air inside a tube is "moving" or "vibrating" without a clear idea of what kind of motion is taking place.

This is one of the reasons (though not the only one) that a tuning fork is used as a sound wave source rather than a speaker. To an expert, the sound source is merely a surface feature that does not affect the physics of the situation; these two sources would serve the same purpose. Students, however, are sometimes thrown off by differences in the surface features of a problem. There is a tendency for students to describe the motion of air particles as "vibrating" without thinking of them as moving longitudinally to both sides of the particle's equilibrium position. In contrast, the tuning fork can be directly seen to move this way, giving the students a mental picture to which they can associate the particle motion.

Appeals to these ideas about motion are then used to identify where motion with the least and greatest amplitude occurs. For example, air particles at the closed end of a

tube are unable to move back and forth because the closed end of the tube is in the way. Thus, the students identify that spot as a displacement node.

Pressure

With their concepts of nodes and antinodes written down, students are then asked about pressure at those different locations. The tutorial describes the following simple mental picture of pressure, which may be a reminder for some students and a new concept for others. Air particles that are more bunched together than normal represent a higher than normal pressure. Likewise, when air particles are more spread out than normal, that represents a lower than normal pressure. In the context of a student debate, the concept of nodes and antinodes of pressure are introduced. Because this is often the first time that students think about nodes and antinodes of something other than displacement, the tutorial addresses the subject with a variety of techniques. Students are asked to sketch the positions of air particles at different times, and complete a table to confirm relationships between nodes and antinodes of both displacement and pressure. Reinforcing that pressure nodes and displacement antinodes happen at the same location in the tube (and vice versa) may seem like pattern-matching, and to some extent that is true. Pattern-matching is not inherently bad, but relying on it alone with a weak understanding of the underlying physics can lead to difficulties. Were the node-antinode table placed earlier in the tutorial, it could add to this difficulty by giving the students a way to remember the node-antinode rule before learning the physics which governs the process.

Resonance as a Special Condition

One of the issues that students have difficulty with is the idea that only tubes of certain lengths will exhibit resonance for a given frequency. To an expert, this seems to be a natural consequence of stating, for example, that open-open tubes resonate whenever the length of the tube is a multiple of half the wavelength of the sound. However, students rarely have firsthand experience with this phenomenon, and we have found that a significant number of students, having heard tubes resonate for a given frequency earlier in the tutorial, extend their model of resonance in a way that allows any frequency to resonate in a column of air. Tutorial section III is included to give students direct experience that not all air columns resonate for all frequencies. The details of particle motion are not addressed in this section, nor is the idea of superposition of waves that are 180 degrees out of phase. The goal is simply to have students recognize that resonance is not just an automatic condition of sound sources and tubes. This idea is revisited in section IV on varied representations of longitudinal standing waves.

Representations of Longitudinal Standing Waves

A major difficulty students must address is the "hybrid" representation of longitudinal standing waves in pipes. Since many students have seen this representation elsewhere, they have preconceptions about what that representation means. Avoiding the topic or asking students not to use such a representation allows those preconceptions to persist, often to the detriment of the student's understanding.

This section of the tutorial appeals to the student's prior work, asking them to directly state whether or not the curves in the hybrid representation represent lines of

motion. This gets across two points: (1) that the curves are not lines of motion, and (2) that the curves must have some other meaning. This second point is one that students will ignore if not directly questioned in this way. Again appealing to prior work in the tutorial, the students describe the motion in terms of a graph of particle displacement away from its equilibrium vs. particle position along the length of the tube. An additional hybrid diagram, similar to one found in some physics texts such as in Knight (2003), follows this explanation where the curves go beyond the borders of the pipe. This picture is one that students in interviews say is incorrectly drawn or does not make sense, because the curves "can't go outside the pipe." The goal is to once again suggest to students that the hybrid diagram is not a picture or cartoon of what is happening in the pipe; instead it is a graph of displacement amplitude vs. position superimposed onto a picture of the pipe. While such a diagram is useful in determining what modes of vibration will fit inside the pipe, it should not be viewed as representing pathways of particle motion.

The hybrid representation is then used in a student debate about the nature of the standing waves in two long pipes. The two pipes represent the two columns of air they use in the tutorial – open-closed pipes, with one three times longer than the other. The pipes are drawn with a half-football (quarter-wavelength) drawn inside, filling the full length of the pipe in both cases. This represents Student 2's idea that the half-football picture is what must be related to sound production, ignoring the idea that the tuning fork used produces a specific frequency, and thus a specific wavelength that does not change between the two pipes. Students working through the tutorial are asked to predict which

student is correct, and often select Student 2's conclusion that the sound heard in the longer tube will be of a lower pitch. The resolution to the debate comes when students actually perform the experiment and hear identical pitches from both air columns. Students also tend to comment on the loudness, since it is often different in the two cases. This can generally be attributed to differences in striking the tuning fork.

The final portion of the tutorial is an open-ended question suggesting a link between the mechanical frequencies of air particles moving back and forth and the tuning fork moving back and forth. The question is an attempt to suggest to the student that it is no coincidence that the frequency of motion of the particles and the frequency heard by the ear should match.

Homework

The Longitudinal Standing Waves Tutorial also includes a short homework that is part practice and part extension of the tutorial. The two main two-dimensional representations for longitudinal standing waves – the "hybrid" pipe-and-curve picture, and the representation of air particles as dots – are both used. As a refresher, the students are first asked to rank the amplitudes of motion of five air particles identified at a variety of spots within the pipe. Using that information, the concept of the dynamic nature of the pressure profile of the air within the pipe is addressed by relating particle motion and pressure once more.

The second part of the homework deals directly with the difficulty of translating one representation into the other. For a given "hybrid" picture, students are presented with a set of four pictures that a fictional student has drawn that represent the locations of

the particles at different moments during their motion. At this point in the instruction, students usually succeed in identifying the error in the picture where air particles have moved toward the curve rather than along the length of the pipe. However, a common error is for the students to identify the picture where air particles are bunched up horizontally at each crossing of the curves as correct. This represents a tendency of the students to take the "hybrid" picture too literally, where the crossing of the curves trigger a response that the air particles should also bunch up at that point. Rather, if the air particles are bunching up at one such crossing, they should be sparser at the next. That picture is also given for the students to consider, and is often identified as an incorrect picture, though at a lesser rate than students identify the "double-bunching" picture as correct.

CHAPTER 6

CURRICULUM IMPACT ON STUDENT LEARNING

At the start of this project, I hoped to create a way to positively impact what students were able to learn about sound and longitudinal standing waves. The evidence I present in this section suggests that this curriculum is a step in the right direction.

Post-instruction Results from the Treatment Section

Typically, Physics 206 classes at Montana State University perform two tutorials on mechanical waves at the beginning of the semester. The tutorials use springs and strings to address concepts of pulse reflection, transmission, and superposition. Students in the Spring 2006 Physics 206 class replaced one of their two wave tutorials with the aforementioned Longitudinal Standing Waves Tutorial. Thus students in the Spring 2006 "treatment" group received the same amount of instructional time studying waves and sound.

Performance on SWDT

By comparing post-instruction results from the Spring 2006 and Fall 2006 Physics 206 classes, we can get a read on how much of an impact the new curriculum had on the students' abilities to grasp longitudinal standing wave concepts.

Table 6. Physics 206 post-instruction overall performance on the SWDT, treatment and non-treatment sections.

	Baseline: Spring 2006, pre-instruction	Fall 2006, post-instruction (non-treatment)	Spring 2006, post-instruction (treatment)
Number of students	176	128	166
Score (out of 22)	7.40	11.34	16.04
Percentage	34%	52%	73%
Gain		3.94	8.64
Average Normalized Gain <G>		0.27	0.59

We can see that the treatment group shows a significant improvement on the SWDT, scoring 73% on the diagnostic and demonstrating a gain of 0.59, which is on the upper end of the medium gain region.

The statistical significance of the difference in post-test scores can be confirmed by applying a t-test to these sets of data. For the difference to be statistically significant at the quite restrictive $\alpha = 0.0005$ level, the t statistic must be above 4.587. The standard deviations of the students' post-instruction scores in the two samples are 2.95 for the non-treatment group and 3.35 for the treatment group. The resulting t-test generates a value of 12.55 for the t statistic, far surpassing the condition for significance at the $\alpha = 0.0005$ level.

Individual Question Performance: Examples

By taking a look at the SWDT results question-by-question, we can also check to see what sort of impact the LSW tutorial has on student performance on specific areas. Table 7 shows the percent of students answering each question on the SWDT correctly for both the non-treatment and treatment Physics 206 sections.

Table 7. Spring 2006 (treatment) and Fall 2006 (non-treatment) Physics 206 scores on individual questions, post-instruction.

		Fall 2006 (non-treatment) (N = 128)	Spring 2006 (treatment) (N = 166)	Difference between scores (treatment %) - (non-treatment%)
Question	Correct response	% correct	% correct	
1	A	64	94	30
2	D	83	89	6
3	A	69	96	27
4	A	65	90	25
5	A	66	93	27
6	A	45	45	0
7	B	87	90	3
8	D	40	58	18
9	A	38	60	22
10	B	58	87	29
11	B	61	81	20
12	B	13	67	54
13	B	45	54	9
14	D	46	74	28
15	C	48	62	24
16	E	17	45	28
17	C	31	56	25
18	B	26	55	29
19	A	38	49	11
20	A	41	75	34
21	A	74	91	17
22	C	80	92	12

In each case, the treatment group scores at least as well as the non-treatment group, and for many of the questions performs dramatically better. Question 12 was one of the most difficult questions as seen by the non-treatment section's post-instruction results. Only 13% of those students answered the question correctly. By contrast, after instruction with the LSW tutorial, two-thirds (67%) of the students in the treatment group answered this question correctly. The critical issue in question 12 is an understanding of

what leads to changing pressure in a resonant pipe. I feel that the major difference in understanding here comes from the experience of visualizing a longitudinal standing wave with the marked slinky in the beginning of the LSW tutorial. It then becomes apparent that displacement nodes are places where the coils (for the spring) or air molecules (for the pipe) are sometimes tightly compressed together and sometimes spread far apart. It is difficult to generate this same experience for a student even in the most lucid of lectures. It is apparent that this is a case where "lecturing more clearly" is insufficient to improve the situation.

Questions 16, 17, and 18, the other most difficult questions as gauged by the performance of the post-instruction Fall 2006 class, also saw large improvements after LSW tutorial instruction.

For some of the questions, there is only a small difference between the treatment and non-treatment post-instruction scores, notably on questions 2, 6, 7, and 13. These small differences are attributable to differing effects. In the case of Questions 2 and 7, students in both treatment and non-treatment post-instruction groups answer with over 80% correct answers. There is minimal room for improvement in this case, and most instructors would be quite pleased to see students answer any question correctly at the 80 to 90% level.

Question 13 involves the range of motion of an individual air molecule at a displacement antinode. While the percentage of correct responses is similar between the treatment and non-treatment sections, the distribution of the answers is not. We see that in the treatment case, virtually all the responses are for longitudinal motions of the

medium (a and b), but many of them incorrectly consider choice (a) to be correct. I believe that this suggests the tutorial was an effective way to emphasize that individual particles of the medium must move along the length of the pipe to create a longitudinal standing wave. However, the use of the slinky at the start of the tutorial could possibly generate some confusion with respect to the range of motion of individual air molecules. It is very possible for students to generate a wave pattern in a slinky where the coils slam together in the middle, then slam to the outer ends of the slinky and vice versa. This could be the reason that (a) looks like such an attractive answer for the treatment group.

Table 8. Answer distribution (percentages) for SWDT Question 13, post-instruction.

	Fall 2006 (non-treatment) (N = 128)	Spring 2006 (treatment) (N = 166)
Response		
a	24	42
b (correct)	45	54
c	14	0
d	7	1
e	9	2

Question 6 is probably the most confusing and interesting of these results. It asks which of two particles (one at a displacement antinode and the other at halfway between antinode and node) will be moving faster while a standing wave is present. The LSW tutorial does not directly address the speed of particles of a medium, but it can be inferred from the differing amplitudes of motion seen for different coils in the slinky, and can also be seen by watching speeds of individual coils of the slinky during its motion. Both post-instruction groups, treatment and non-treatment, answer 45% correctly. The LSW

tutorial is only a small change to the total curriculum, so it is reasonable that it might not effect change on every single longitudinal wave concept.

The interesting difference here is that the dominant wrong choice differs between the two groups. The non-treatment groups select the other particle (the one halfway between node and antinode) as the dominant incorrect answer, while treatment students choose that both particles move at the "speed of sound" for their answer. The resolution to that issue is unclear makes for an interesting point a from which to continue this work.

Table 9. Answer distribution (percentages) for SWDT Question 6, post-instruction.

	Fall 2006 (non-treatment) (N = 128)	Spring 2006 (treatment) (N = 166)
Response		
a (correct)	45	45
b	30	7
c	11	31
d	13	17
Other / No response	1	0

Anecdotal Evidence for Learning

I had the opportunity to watch and interact with many students as they worked through the LSW tutorial, and witnessed some very important things that affected students' learning about sound and longitudinal standing waves. One of the most direct instances of this is LSW Section III, a short section where students remove water from an upright pipe which prior to the removal generated a loud tone when a tuning fork was placed over the pipe. They then try to generate a standing wave with the tuning fork and were often shocked to find that they were unable to do so. It is clear that many students

prior to the tutorial expect resonance to happen in this situation regardless of the mismatch between the natural frequencies of the pipe and the frequency of the tuning fork. Perhaps more appropriately, these students do not recognize a conflict exists, merely relying on the fragment stating, " tuning forks make tubes produce sound."

Also, from discussions with students participating in the laboratory, their understanding of the hybrid representation of a standing wave in a pipe is much improved. Section IV, part B involves the infamous "sine curve outside the pipe walls" question. When students get to this section, it was my experience that they were much better equipped to answer the question than without the LSW tutorial. Recall that this is the same question that 14 of 14 students in the preliminary interviews were unable to make sense of.

Student comments I received were also positive evidence of impact on the learning process. Loosely paraphrasing one of these student comments, he claimed that he thought this tutorial was a waste of time, but then he realized he was learning something and so that was OK.

CHAPTER 7

CONCLUSIONS

My concerns about teaching the subject of longitudinal standing waves as a mere pattern matching exercise and extension of transverse standing waves started me on a journey to see if there was some way to improve student understanding on a subject that is all too often glossed over by physics instructors. At this point I look back and review the questions and main conclusions of this journey.

What are the Main Student Difficulties in Understanding Longitudinal Standing Waves?

One source of the difficulties students have with the physics content of this subject stem from their usage of small fragments of reasoning to build their understanding. Survey and interview data reveal that students do not have a strong commitment to their initial understanding of sound and longitudinal standing waves, which is consistent with using a fragmented set of p-prims and other small-scale knowledge structures as a way to attempt to build an initial understanding of this subject. This lack of an overarching model for sound and longitudinal standing waves thus requires the student to try to make sense of these phenomena with the other resources they have available.

Another major source of difficulty is the problematic hybrid representation of longitudinal standing waves in pipes, where a graph of longitudinal displacement is plotted along the primary axis of a pictured pipe. This representation is very memorable

and nearly impossible to ignore, yet at the same time is misleading to the student. It generates difficulties in the form of incorrect predictions of the motions of air molecules within the pipe, among others.

The extent to which students have problems with longitudinal standing waves can be gauged by performance on the Standing Wave Diagnostic Test, created as a part of this investigation. For the introductory algebra-based Physics 206 classes at Montana State University, a baseline score of 7.40/22 was used for the pre-instruction score. The non-treatment sections scored 11.34/22 on the SWDT post-instruction, demonstrating a low-gain normalized gain of 0.27.

What Can Be Done to Impact Student Understanding?

The aforementioned difficulties must be addressed in a way that goes beyond teaching by telling. An interactive engagement, University of Washington – style tutorial was developed in an effort to provide a more effective way of teaching longitudinal standing waves. The Longitudinal Standing Waves Tutorial was used with students in algebra-based Physics 206 classes, whose understanding was also gauged by performance on the Standing Wave Diagnostic Test. This treatment group scored 7.40/22 on the SWDT pre-instruction and 16.04/22 on the SWDT post-instruction, realizing a upper-medium level normalized gain of 0.59.

In Conclusion

The results from the SWDT and LSW provide a positive outlook the teaching and learning of sound and longitudinal standing waves. They suggest that effective measures can be taken to help students to create a better model for longitudinal standing waves. It also provides a way to understand the physics resonant pipes rather than just the rote formulae for open-open and closed-open pipes. In addition, this project demonstrates the usefulness of the Physics Education Research process of using research to create curriculum that impacts instruction. That process of instruction can then become a vehicle for more research, allowing the cycle to continue, generating subsequent improvements.

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APPENDICES

APPENDIX A

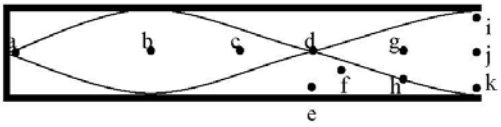
SURVEY INSTRUMENTS

APPENDIX A-1: Physics 211 survey, December 2003, version 1

Physics 211 In-class Activity 12/8/03

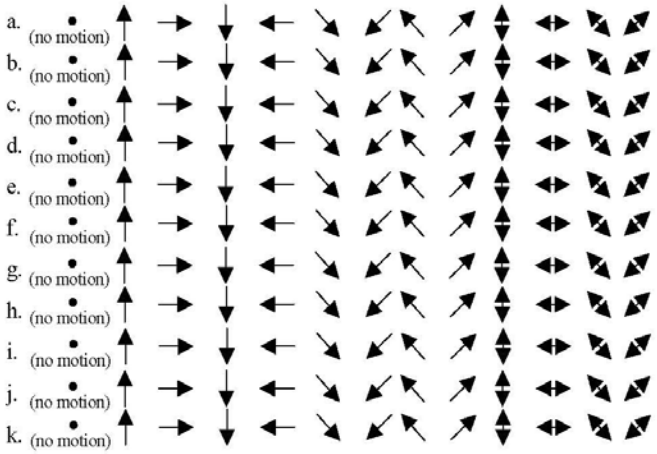
Name:_____

Row:_____



Above is a picture of a metal pipe closed at one end, resonating as shown. You might find such a picture in a physics textbook in the section about sound. The following questions ask about the air particle motions occurring inside this pipe. Ignore any random thermal motion of the particles in these questions.

1) For each of the positions a-k above, circle the arrow that describes the direction of motion of air molecules at those positions when the pipe is resonating:



2) Describe what was useful about the picture above and how you used it to select your arrows.

3) In question 1, some air particles move more than others. In the following comparisons, circle which air molecule moves **farther** (with a greater amplitude) than the other, or circle "same" if they move the same amount.
   a. **Particle a , particle b, same**
   b. **Particle a , particle d, same**
   c. **Particle b , particle c, same**
   d. **Particle d , particle e, same**
   e. **Particle d , particle h, same**
   f. **Particle d , particle j, same**
   g. **Particle g , particle h, same**
   h. **Particle g , particle j, same**
   i. **Particle j , particle k, same**

(continued on back)

4) When the pipe is resonating and particle **c** is displaced to the right, where is particle **g**?
   a. Displaced to the right
   b. Displaced to the left
   c. Not displaced
   d. It could be any of the above.

   Explain your answer.

5) Sketch two different standing waves in the pipe below (open at both ends). **Explain** what the lines in your sketch represent.

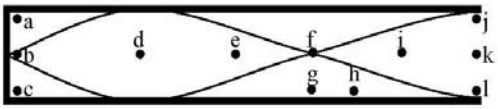
6) The pipe from question 5 is now placed in a room filled with helium, which has a smaller molecular mass than air. This makes the speed of sound in helium about 3 times faster than air. Sketch this pipe's fundamental **and** explain why you drew it as you did.

APPENDIX A-2: Physics 211 survey, December 2003, version 2

Physics 211 In-class Activity 12/8/03

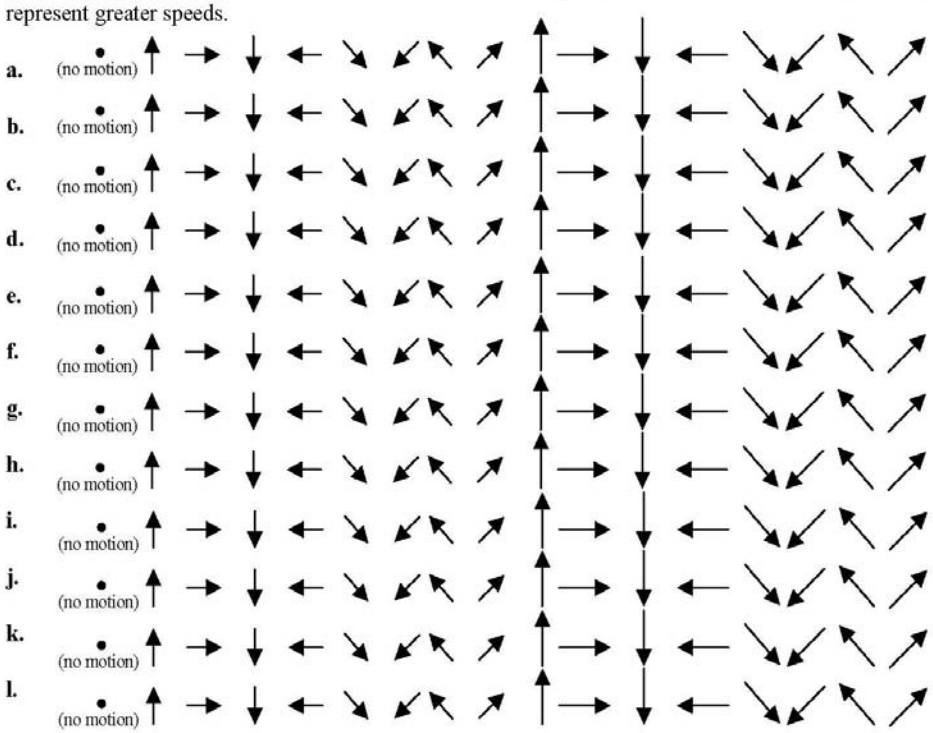
Name:_____

Row:_____



Above is a picture of a metal pipe, closed at one end, resonating as shown. You might find such a picture in a physics textbook in the section about sound. The following questions ask about the air particle motions occurring inside this pipe. Ignore any random thermal motion of the particles in these questions.

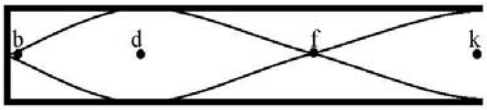
1) Imagine that we take a snapshot of the air molecules in the pipe so that we can see what each molecule is doing for an instant in time. **We find that the molecule at position d is moving to the left.** For each position (a-l), circle the arrow that best represents the velocity of the air molecules. The longer arrows represent greater speeds.



2) Describe what was useful about the picture above and how you used it to select your arrows.

(continued on back)

3) At how many of the points shown (b,d,f,k) is the air pressure changing while the pipe is resonating? Explain your answer.



4) What is the average pressure at each of the points in the pipe when it is resonating?

Point b:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

Point d:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

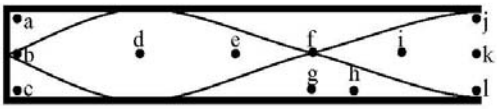
Point f:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

Point k:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

5) Describe the process by which the sound gets from the resonating pipe to your ears so that you can hear the pipe. Within your description, tell what the air particles between you and the pipe are doing.

APPENDIX A-3: Physics 206 pre-instruction survey, January 2004

Physics 206 survey - Jan '04 Name:_____



Above is a picture of a metal pipe, closed at one end, resonating as shown. You might find such a picture in a physics textbook in the section about sound. The following questions ask about the air particle motions occurring inside this pipe. Ignore any random thermal motion of the particles in these questions.

For each question, rate how confident you are that your answer is correct (on a scale of 1 to 5). 1 is just guessing, and 5 represents that you are confident that your answer is correct.

1) Imagine that we take a snapshot of the air molecules in the pipe so that we can see what each molecule is doing for an instant in time. **We find that the molecule at position d is moving to the left.** For each position (a-l), circle the arrow that best represents the velocity of the air molecules.

a. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

b. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

c. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

d. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

e. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

f. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

g. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

h. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

i. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

j. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

k. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

l. (no motion) ↑ → ↓ ← ↘ ↙ ↖ ↗

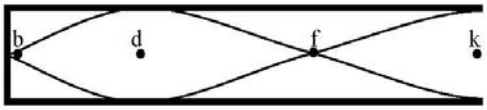
Rate your confidence for this question (1 is guessing, 5 is very confident) _____

2) Compare particles **i** and **k**. Do you think one would be moving faster than the other (and if so, which is faster), or do they move at the same speed? Explain.

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

(continued on back)

3) At how many of the points shown (b,d,f,k) is the air pressure changing while the pipe is resonating (making a sound)? Explain your answer.



Rate your confidence for this question (1 is guessing, 5 is very confident) _____

4) What is the average pressure at each of the points in the pipe when it is resonating?

Point b:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

Point d:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

Point f:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

Point k:
   a. above atmospheric pressure
   b. same as atmospheric pressure
   c. below atmospheric pressure, but not zero pressure
   d. zero pressure

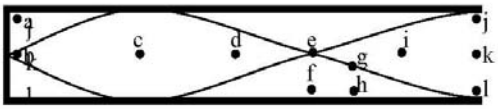
Rate your confidence for this question (1 is guessing, 5 is very confident) _____

5) Describe the process by which the sound gets from the resonating pipe to your ears so that you can hear the pipe. Within your description, try to describe what the air particles between you and the pipe are doing.

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

APPENDIX A-4: Physics 206 post-instruction survey, March 2004

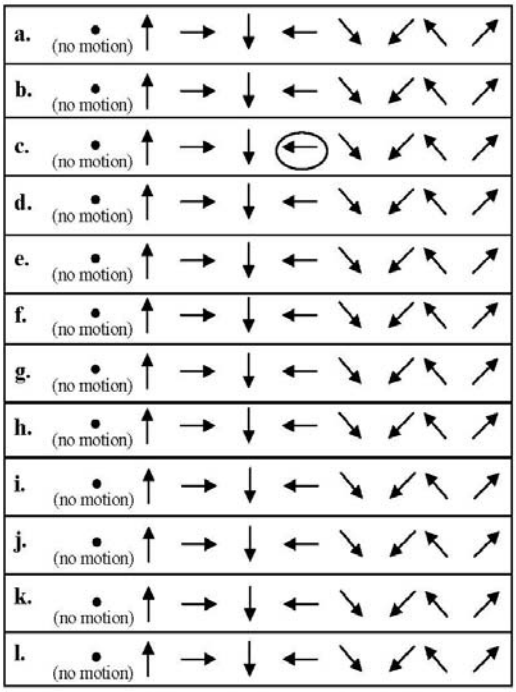
Physics 206 survey - Mar '04 Name:_____



Above is a picture of a resonating metal pipe that is closed at one end. You might find such a picture in a physics textbook in the section about sound. The following questions ask about the motions of some of the air particles inside this pipe. Ignore any random thermal motion of the particles in these questions.

For each question, rate how confident you are that your answer is correct (on a scale of 1 to 5). 1 is just guessing, and 5 represents that you are very confident that your answer is correct.

1) Imagine that we take a snapshot of the air molecules in the pipe so that we can see what each molecule is doing for an instant in time. **We find that the molecule at position c is moving to the left.** The appropriate arrow is already circled below for the air molecule at point c. For each position (a-l), circle the arrow that best represents the velocity of the air molecules.



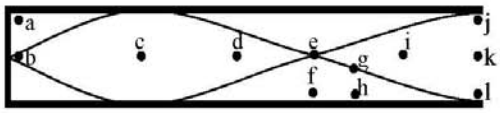
Rate your confidence for this question (1 is guessing, 5 is very confident) _____

2) Compare particles **i** and **k**. Do you think one would be moving faster than the other (and if so, which is faster), or do they move at the same speed? Explain.

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

(continued on back)

3) For each point listed below, which choice best describes the air pressure at that point while the pipe is resonating? You may use choices more than once. (The diagram is the same as the one on the first page.)



CHOICES:

a. The pressure stays the same and is above atmospheric pressure
b. The pressure stays the same and is the same as atmospheric pressure.
c. The pressure stays the same and is below atmospheric pressure
d. The pressure is changing and is generally above atmospheric pressure
e. The pressure is changing and is generally below atmospheric pressure
f. The pressure is sometimes above and sometimes below atmospheric pressure

Point b:

Point c:

Point e:

Point k:

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

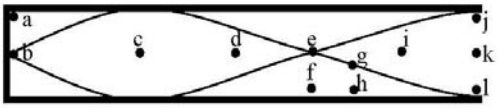
4) In the diagram above, some air particles move more than others. In the following comparisons, determine which air particle moves **farther** (with a greater amplitude). Circle the letter of the particle that moves with the greater amplitude in each comparison. If the particles have the same amplitude, circle "same amplitude."

Comparison	Which has the greater amplitude?		
a ↔ b	a	b	same amplitude
c ↔ d	c	d	same amplitude
c ↔ k	c	k	same amplitude
e ↔ g	e	g	same amplitude
f ↔ g	f	g	same amplitude
g ↔ i	g	i	same amplitude
h ↔ l	h	l	same amplitude

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

APPENDIX A-5: Physics 211 post-instruction survey, April 2004

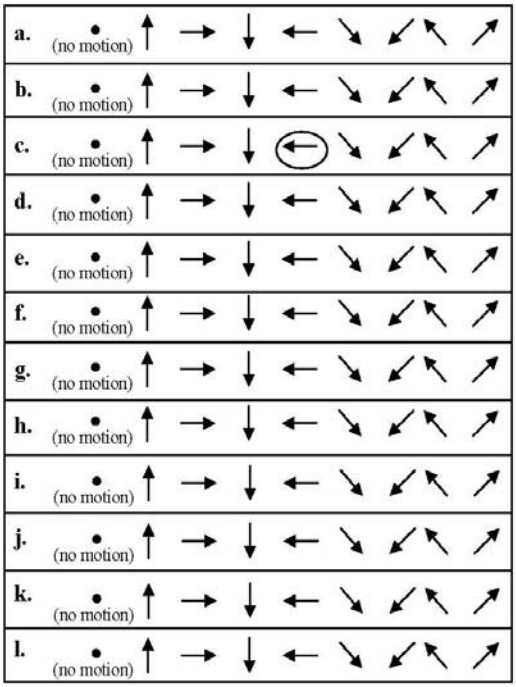
Physics 211 survey - Apr '04 Name:_____



Above is a picture of a resonating metal pipe closed at one end. Some of the air particles inside are also labeled. You might find such a picture in a physics textbook in the section about sound. The following questions ask about the motions of some of the air particles inside this pipe. Ignore any random thermal motion of the particles in these questions.

For each question, rate how confident you are that your answer is correct (on a scale of 1 to 5). 1 is just guessing, and 5 represents that you are very confident that your answer is correct.

1) Imagine that we take a snapshot of the air molecules in the pipe so that we can see what each molecule is doing for an instant in time. **We find that the molecule at position c is moving to the left.** The appropriate arrow is already circled below for the air molecule at point c. For each position (a-l), circle the arrow that best represents the velocity of the air molecules.



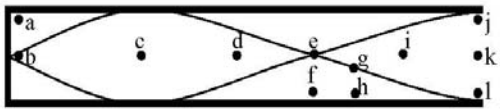
Rate your confidence for this question (1 is guessing, 5 is very confident) _____

2) Compare particles i and k. Do you think one would be moving faster than the other (and if so, which is faster), or do they move at the same speed? Explain.

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

(continued on back)

3) For each point listed below, which choice best describes the air pressure at that point while the pipe is resonating? You may use choices more than once. (The diagram is the same as the one on the first page.)



CHOICES:

a. The pressure stays the same and is above atmospheric pressure
b. The pressure stays the same and is the same as atmospheric pressure.
c. The pressure stays the same and is below atmospheric pressure
d. The pressure is changing and is generally above atmospheric pressure
e. The pressure is changing and is generally below atmospheric pressure
f. The pressure is sometimes above and sometimes below atmospheric pressure

Point b:

Point c:

Point e:

Point k:

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

4) In the diagram above, some air particles move more than others. In the following comparisons, determine which air particle moves **farther** (with a greater amplitude). Circle the letter of the particle that moves with the greater amplitude in each comparison. If the particles have the same amplitude, circle "same amplitude."

Comparison	Which has the greater amplitude?		
a ↔ b	a	b	same amplitude
c ↔ d	c	d	same amplitude
c ↔ k	c	k	same amplitude
e ↔ g	e	g	same amplitude
f ↔ g	f	g	same amplitude
g ↔ i	g	i	same amplitude
h ↔ l	h	l	same amplitude

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

5) The pipe above is resonating at a frequency of 10 Hz. Look at the air particle lettered **d**. With what frequency does the air particle at **d** oscillate inside the pipe?

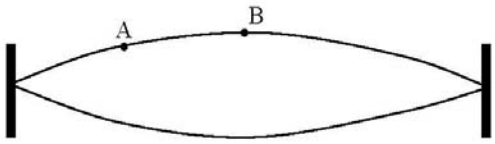
a. 10 Hz
b. varies between 5 and 10 Hz
c. 5 Hz
d. varies between 0 and 5 Hz
e. The particle moves, but does not have a frequency
f. The particle does not move

Rate your confidence for this question (1 is guessing, 5 is very confident) _____

APPENDIX B

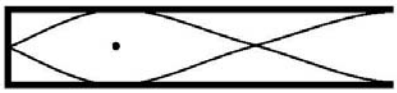
PHYSICS 211 EXAM QUESTIONS, SPRING 2004

1. A string is clamped at both ends and plucked, making it vibrate at its fundamental frequency. Consider two points on the string. How do the speeds of the two points compare?



   a. A is generally moving faster than B.
   b. B is generally moving faster than A.
   c. Both points move at the speed of sound.
   d. Both points move at the same speed, but not necessarily the speed of sound.

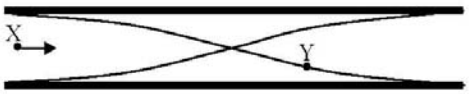
2. Consider the air molecule (shown by the black dot) in the closed-open pipe at right. The pipe resonates as shown. At what position will it move its fastest?



   a. When it reaches the open end of the pipe
   b. When it reaches the closed end of the pipe
   c. When it is at its maximum displacement from its original position
   d. Halfway between its original position and its maximum displacement
   e. When it returns to its original position

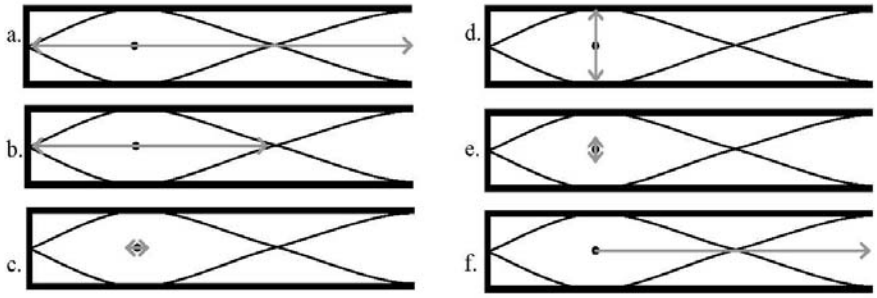
3. Two pipes are resonating at a frequency of 50 Hz. One has both ends open, and the other has one end closed and one end open. Consider air particles A (in the open-open pipe) and B (in the open-closed pipe). A and B are located halfway between a node and antinode in their respective pipes. With what frequencies are the two air particles oscillating back and forth inside their respective pipes?
   a. 50 Hz for particle A, 50 Hz for particle B
   b. 50 Hz for particle A, 25 Hz for particle B
   c. 25 Hz for particle A, 50 Hz for particle B
   d. 25 Hz for particle A, 25 Hz for particle B
   e. A frequency can not be assigned to particles A and B

4. The open-open pipe at right resonates as shown. At one moment in time, the air particle at X is moving to the right as shown. Which way will the particle at Y be moving at that moment?

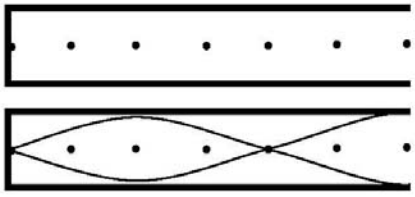


   a. Along the line, toward the center
   b. Along the line, toward the right end
   c. up
   d. down
   e. horizontally left
   f. horizontally right

5. A pipe that is closed at one end is resonating as shown. The small black dot represents one of the air particles inside the pipe. Which of the following best describes the movement of the air particle while the pipe is resonating?



6. The top pipe shows seven equally spaced air particles inside the pipe. The dots represent their positions **before** the pipe is made to resonate. If the pipe resonates (as in the bottom pipe), and at a later time we see the particles in the same positions, what can we say about the pressure inside the pipe?



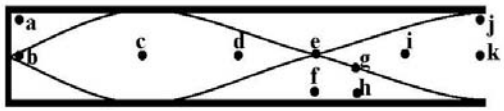
   a. The pressure is the same throughout the pipe
   b. The pressure is higher at the displacement nodes and lower at the displacement antinodes
   c. The pressure is lower at the displacement nodes and higher at the displacement antinodes

APPENDIX C

STANDING WAVE DIAGNOSTIC TEST

Standing Wave Diagnostic Test

Below is a picture of a standing wave in a resonating pipe that is closed at one end. You might find such a picture in a physics textbook in the section about sound. Several positions inside the pipe are labeled. Use this diagram for questions 1-8 that ask about the motions of air particles at these positions. Ignore any random thermal motions of the particles in these questions.



For questions 1-5, select the choice that best describes the direction of motion of air particles at the position indicated:

1. Position **c**:
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Not moving

2. Position **e**:
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Not moving

3. Position **g**:
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Not moving

4. Position **j**:
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Not moving

5. Position **h**:
   a. Horizontal
   b. Vertical
   c. Diagonal
   d. Not moving

6. Consider air particles at locations **c** and **d** in the pipe. How do the speeds of the two particles compare?
   a. **c** is generally moving faster than **d**.
   b. **d** is generally moving faster than **c**.
   c. Both particles move at the speed of sound.
   d. Both particles move at the same speed, but not necessarily the speed of sound.

7. The air particle at position **d** is observed at a particular moment and is seen moving to the right. Which way would the air particle at position **i** be moving at that same moment?
   a. right
   b. left
   c. up
   d. down
   e. not enough information to tell

8. Assume that we measure the air pressure at point **c** at a moment while the pipe is resonating and find it to be 1 atm (standard atmospheric pressure). If we measured the pressure at point **c** at a later time, what possible values might we measure?
   a. Above 1 atm
   b. Below 1 atm
   c. Both above and below 1 atm
   d. 1 atm only (no change)

(continue next page)

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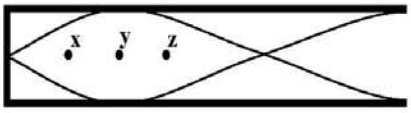
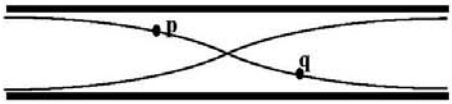
9. In the resonating pipe shown, the air particle at position **z** moves to the left. What best describes the motion of the particle at position **x** at that moment?



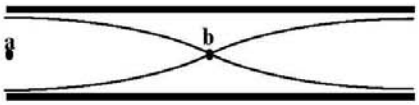
   a. moves left
   b. moves right
   c. moves up
   d. moves down
   e. does not move

10. A pipe open at both ends is made to resonate as shown. Which statement best describes the motion of air particles at points **p** and **q**?



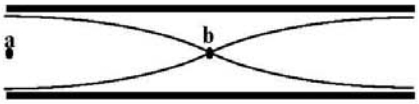
   a. They always move in opposite directions and move along the curve
   b. They always move in opposite directions and move horizontally
   c. They always move in opposite directions and move vertically
   d. They always move in the same direction and move along the curve
   e. They always move in the same direction and move horizontally

11. While this pipe is resonating in the mode shown, where will the **highest** pressures occur in the pipe?



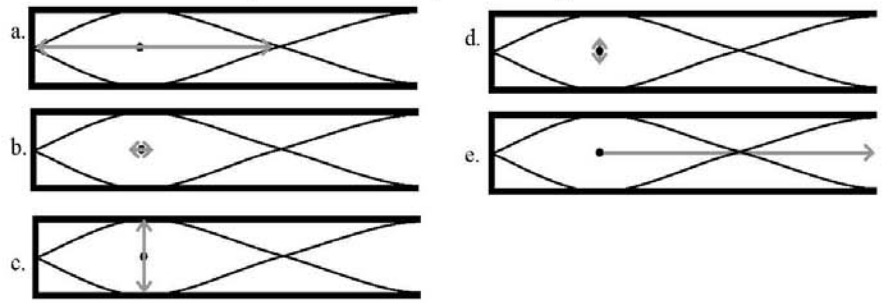
   a. At **a**
   b. At **b**
   c. At both **a** and **b**
   d. Somewhere else (neither **a** nor **b**)

12. While this pipe is resonating in the mode shown, at which of these two points will the pressure be changing?



   a. At **a**
   b. At **b**
   c. At both **a** and **b**
   d. Neither **a** nor **b**

13. A pipe that is closed at one end is resonating as shown. The small black dot represents one of the air particles inside the pipe. Which of the following arrows best describes the movement of the air particle while the pipe is resonating?



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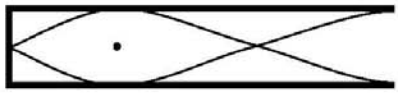
14. A speaker produces a 400 Hz sound. When it is brought near the end of a long pipe that is open at both ends, no additional sound is heard. How could the speaker's volume be adjusted to cause the pipe to resonate?
    a. Increase volume
    b. Decrease volume
    c. Both a and b
    d. Neither a nor b

15. A speaker is attached to a frequency generator so that its frequency can be adjusted. The speaker is brought near the end of a short pipe open at both ends, which resonates loudly. The speaker is then brought near a long pipe open at both ends, but the pipe produces no sound. How could the speaker's frequency be adjusted to cause this longer pipe to resonate?
    a. Increase frequency
    b. Decrease frequency
    c. Both a and b
    d. Neither a nor b

16. Consider the air molecule (shown by the black dot) in the pipe at right. The pipe resonates as shown. At what position will the air molecule move the fastest?



    a. When it reaches the open end of the pipe
    b. When it reaches the closed end of the pipe
    c. When it is at its maximum displacement from its original position
    d. Halfway between its original position and its maximum displacement
    e. When it returns to its original position

17. A pipe closed at one end and open at the other is made to resonate at its fundamental frequency. At a particular moment, the air pressure just inside the closed end is measured and is found to be 1 atm (standard atmospheric pressure). If the pressure were measured at that location at a later time, what other possible values might be measured?
    a. Above 1 atm
    b. Below 1 atm
    c. Both above and below 1 atm
    d. 1 atm only (no change)

18. Consider a resonating pipe with one end open and one end closed. Starting from the open end of the pipe, how does the motion of the air particles change as you move toward the closed end of the pipe?
    a. The frequency of their oscillations change
    b. The amplitude of their oscillations change
    c. Both a and b
    d. Neither a nor b

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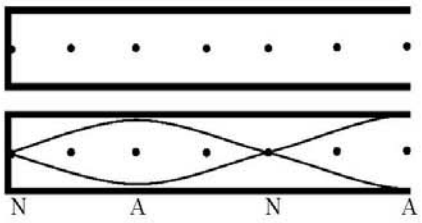
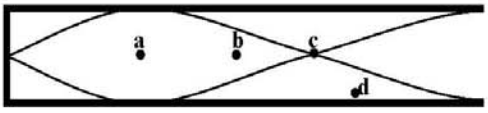
19. The top pipe shows seven equally spaced air particles inside the pipe. The dots represent their positions **before** the pipe is made to resonate. If the pipe resonates (as in the bottom pipe), and at a later time we see the particles in the same positions, what can we say about the pressure inside the pipe?



    a. The pressure is the same throughout the pipe
    b. The pressure is higher at the nodes and lower at the antinodes
    c. The pressure is lower at the nodes and higher at the antinodes

20. Two different pipes are resonating at a frequency of 50 Hz. Pipe A has both ends open, and Pipe B has one end closed and one end open. The pipe with one end closed is half as long as the pipe with both ends open. Consider an air particle at an antinode in each pipe. With what frequencies are the two air particles oscillating back and forth inside their respective pipes?
    a. 50 Hz in A, 50 Hz in B
    b. 50 Hz in A, 25 Hz in B
    c. 25 Hz in A, 50 Hz in B
    d. 25 Hz in A, 25 Hz in B
    e. A frequency can not be assigned to particles in Pipes A and B



Use the picture above with questions 21 and 22.

21. Which of the following particles move with the **largest** amplitude?
    a. **a**
    b. **b**
    c. **c**
    d. **d**

22. Which of the following particles move with the **smallest** amplitude?
    a. **a**
    b. **b**
    c. **c**
    d. **d**

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APPENDIX D

LONGITUDINAL STANDING WAVES TUTORIAL AND HOMEWORK

LONGITUDINAL STANDING WAVES

I. Motion in standing waves

Obtain a coiled spring (Slinky) and a large sheet of paper. On the paper, stretch the spring so that each coil of the spring is about 1 cm away from the next. You may not have to use the entire length of the slinky to do this. Draw a straight line under your spring along its length to indicate its position at rest.

Stick small pieces of tape to the tops of several individual coils of the spring. This may already be done; add pieces as needed. These tape strips will act like small markers or flags. Mark the positions of these tape strips on the line you drew on the paper.

A. With one person holding both ends of the spring, demonstrate how to produce a fundamental transverse standing wave with the spring. Do the tape flags move:

- parallel or perpendicular to the length of the slinky?
- above the center line? below the center line?
- differently for tape flags near the ends of the spring compared to those in middle of the spring? Describe that difference in motion.

In a standing wave, some parts of the medium move with large amplitude, while others have essentially no motion. The places where these occur are called **displacement antinodes** and **displacement nodes** respectively.

B. **Predict** the motions of the individual tape flags on the spring if you were to produce a **longitudinal** standing wave by moving your hands inward and outward. Sketch these predictions on your large sheet of paper.

With one person holding both ends of the spring, produce a **longitudinal** standing wave with the spring. Observe the motion of individual tape flags.

- Do the tape flags move parallel or perpendicular to the length of the slinky? Describe the motion of an individual tape flag relative to its equilibrium position.

- **Circle** those positions where tape flags appear to be moving the most (with greatest amplitude).
- **Draw a box** around those positions where tape flags appear to be moving the least or not at all.

Just like transverse standing waves, longitudinal standing waves also have displacement nodes and antinodes.

- On your large sheet, label the positions of these displacement nodes "N" and antinodes "A".

C. Have a member of your group reproduce your longitudinal standing wave. Find a node where a tape flag is not moving. Watch the coils immediately to the right of that position. If needed, tape-flag some of these individual coils in order to see their motion more easily.

- Do these coils move with the same amplitude or different amplitudes? (If you aren't sure, reproduce the motion. Try watching specific coils near the node.)

Consider the following student statements:

Student 1: *A longitudinal standing wave means every part of the spring moves the same distance back and forth because I move my hands the same distance each time. The point in the middle is a node, so it doesn't move.*

Student 2: *If every part of the spring moved the same distance, the parts of the spring near the node would go too far and go past the node, so I think that the parts of the spring closer to the node move with a smaller amplitude.*

With which of the statements, if any, do you agree? Explain.

⇨ Discuss your answers with a tutorial instructor

II. Longitudinal waves in pipes – air motion and pressure

The longitudinal waves on the spring in Part I are a good analogy for the motions of air particles in a tube when a standing sound wave is produced.

A. Produce a sound with the tuning fork. Use the felt pad provided – knocking the fork directly on the table produces unwanted extra noise and can damage the fork. Hold the tuning fork to your ear, and remember the sound. Repeat for all group members.

B. Use the tuning fork to create a standing wave in a tall cylinder. Fill the cylinder with water until the water level is at the top mark. Knock the tuning fork on the felt pad again and hold it just over the opening of the cylinder. You should hear a loud tone when the standing wave is present.

- How does the pitch (frequency) of this sound compare to when you held the tuning fork to your ear?

- Where in the cylinder would the air particles be unable to move up and down along the tube? Would this be a displacement node or antinode? Explain.

- Where in the cylinder would you expect to find a displacement antinode? Explain.

- At right, indicate the locations of the displacement nodes and antinodes you described above

When the particles in the tube are moving, consider how that motion affects the pressure in the tube. When air particles are more closely bunched together, it results in higher than normal pressure. Likewise, when the air particles are more sparse than normal, that represents a lower pressure.

B. Consider the following student comments about pressure in the cylinder:

Student 1: *The pressure at the bottom of the tube is always higher than normal. Air particles keep pushing down there because of the standing wave.*

Student 2: *Sometimes the air particles are moving toward the bottom, but they would also move away from the bottom sometimes – they're like the slinky's coils; they have to go both back and forth. So the pressure at the bottom must be sometimes higher and sometimes lower than normal.*

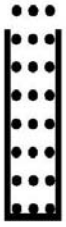
With which of the statements, if any, do you agree? Explain.

C. A third student comments about what was said by Student 2:

Student 3: *If the pressure is sometimes higher and sometimes lower than normal, that's like an antinode – but for pressure, not displacement. So where there's a displacement node, there's also a pressure antinode at the same spot.*

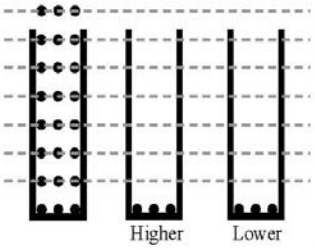
Do you agree or disagree with this student statement? Explain.

We can represent what the air particles are doing inside (and outside) the cylinder by drawing some of the air particles and seeing how their positions change while the standing wave is present. The picture at right represents positions of some of the air particles when they are at their equilibrium positions. This is like the coils of the slinky in Part I, which were evenly spaced before any standing wave was produced.



Imagine that there is now a standing wave present in the tube, and you take a snapshot showing where each of the air particles is.

- Sketch what you think the positions of these air particles would be if the pressure were <u>higher</u> at the bottom of the tube.
- Sketch what you think the positions of these air particles would be if the pressure were <u>lower</u> at the bottom of the tube.



Consider the following student statement:

Student: *At the top of the pipe, there's a displacement antinode, so the air particles move more than at the bottom. But the pressure should stay the same – it's closest to the outside, so it's at atmospheric pressure. So the pressure must not be changing, and the particles aren't bunching up or spreading out.*

Do you agree or disagree with this statement? Explain.

We can represent what is happening inside the pipe in terms of displacement nodes and antinodes, or in terms of pressure nodes and antinodes. At places where particle motion is minimal (displacement nodes), pressure can go up and down (pressure antinodes). Likewise, where the amplitude of particle motion is a maximum (displacement antinodes), the pressure doesn't really change (pressure nodes).

D. Summarize what you know about displacement and pressure nodes and antinodes in the table below. Write "node" or "antinode" in each box to represent which type of node/antinode is present in each location.

Type of node/antinode:	Particles move with greatest amplitude	Particles are stationary
Displacement		
Pressure		

⇨ Discuss your answers with a tutorial instructor

III. Longitudinal waves in pipes of differing lengths

A. Suppose that you continued to fill the tall cylinder used in Part A so that the water level was halfway between the top mark and the top of the cylinder. **Predict** what you will hear when a ringing tuning fork is held over the opening of such a cylinder. Write your prediction below, indicating any differences in frequency and loudness compared to part A.

B. Add water to the cylinder until the water level is halfway between the top mark and the top of the tube. Ring the tuning fork and hold it over the cylinder. Record your results.

- Do the tuning fork and pipe produce the same sound as in part A?

⇨ Discuss your answers with a tutorial instructor

The standing wave phenomenon you have seen earlier in this tutorial only occurs for air columns of specific lengths. Your text can provide you with a more detailed account of the conditions necessary for resonance.

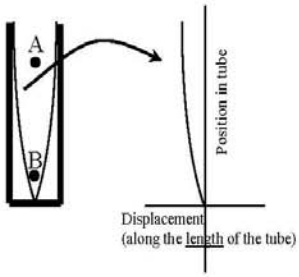
IV. Understanding other representations

A. The representation of a standing wave at right is often seen in textbooks.

- Based on your work so far in this tutorial, do you think that the curved lines represent the paths along which air particles will travel? Explain.

The curved lines inside the cylinder are useful if used in the right context. We have seen that air particles aren't able to move when against the base of our cylinder, so there is a displacement node there. The curves tell us the same thing if we view them on a displacement vs. position graph:

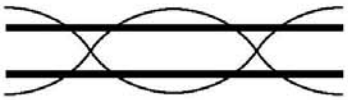
It's a little strange, because this graph is drawn with an amplitude that looks like particles move toward the side wall of the cylinder. But from our prior work, we see that the motions of our particles are <u>along</u> the cylinder, not toward the sides.



- Consider the picture at right. Which particle moves farther <u>along</u> the cylinder, the particle at position A, B, or neither?
- Which particle moves farther <u>toward the side walls</u> of the cylinder: A, B, or neither?

This is sometimes referred to as a "football" representation, because the curves look football-shaped. Where the football is the widest, the particles have the largest displacement amplitude.

B. Consider the student statements below regarding the picture of a pipe that is open at both ends.



Student 1: *This picture must be a mistake. The air particles can't go outside the tube, so this wave can't happen.*

Student 2: *I think they are just trying to show us where the nodes and antinodes are. The curve just means the particles on the ends and middle move the most. The particles never actually cross through the pipe because they move along the pipe.*

With which of the statements, if any, do you agree? Explain.

C. Later in this part, you will empty the cylinder so that the water level is even with the lower line marked on the cylinder. But first, do the following:

Predict what you will hear if you use your same tuning fork to attempt to produce a sound with the water level at the lower marking on your cylinder.

- Consider the following student comments:

Student 1: *The sound should be the same in both cylinders. The number of Hz is marked on the tuning fork, so that's the only sound we can get.*
Student 2: *Look at my picture on the right. You're forgetting that the cylinder is longer now, so our sound will have a longer wavelength. That means the sound will be much lower because of the longer wavelength.*

With which of the student statements, if either, do you agree? Explain.

- Perform the experiment. Empty the cylinder to the lower line and use the tuning fork to make a sound. Record your observations, and check your predictions.

⇨ Discuss your answers with a tutorial instructor

V. Particle motion and frequency

A. Consider the following student comment:

Student: *The number of Hz on the tuning fork tells you how many times the fork moves back and forth, so that's how many times the air particles get pushed back and forth. That means the air particles move with the same frequency as the tuning fork.*

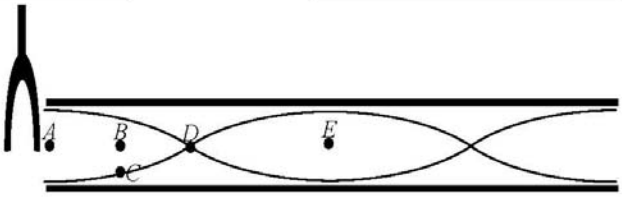
Is this student correct? Discuss why or why not.

⇨ Discuss your answers with a tutorial instructor

LONGITUDINAL STANDING WAVES Name _____

Homework

1. A tuning fork and a tube with both ends open are used to produce a standing sound wave as shown. Locations of some of the air particles in the tube are marked as shown. Before the standing wave was produced, we can assume that the pressure inside the tube is atmospheric pressure (1atm).



   a. Rank the displacement amplitudes of particles A-E from largest to smallest. Explain your reasoning.

   b. For the points listed below, answer the following questions and explain your answer.

      While the standing wave is present, does the pressure at this point *remain constant* or is it *changing* throughout the cycle?

      If constant, is it always below atmospheric pressure, at atmospheric pressure, or above atmospheric pressure? If changing, is it always below atmospheric pressure, always above atmospheric pressure, or sometimes below and sometimes above?

      Point A:

      Point D:

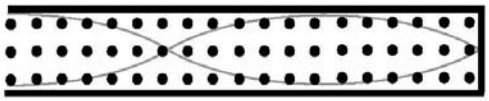
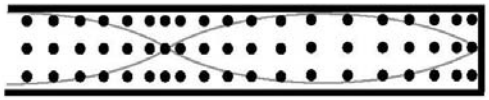
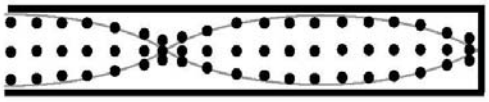
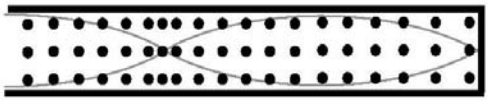
   c. Compare the direction of motion of air particles at points B and C. What, if anything, is different about their motions?

      Consider an air particle that starts out at point B. When a standing wave is present in the tube, will the air particle at B move *up, down, left, right,* or more than one of these? Explain.

   d. Compare the direction of motion of air particles at points A and E. What, if anything, is different about their motions?

LONGITUDINAL STANDING WAVES Name _____
Homework

2. Consider the standing wave present in the tube shown. A student tries to draw representations of the air particles inside the pipe at various times while this standing wave is present.

a. Do these curves represent displacement amplitude or pressure amplitude? Explain how you can tell.

b. For each of the four drawings below, determine if there is a flaw. If so, identify and describe the flaw. If the drawing correctly represents the air particles at some instant, indicate the positions of the **pressure** nodes and antinodes in the tube. (Label the nodes "N" and antinodes "A".)