IDENTIFYING STUDENTS' MENTAL MODELS OF SOUND PROPAGATION

by

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ABSTRACT

We investigated students' mental models of sound propagation in a concept-based introductory physics class. We found that in addition to the scientifically accepted wave model, students used the "entity" model as a dominant alternative model. In this model sound is a self-standing entity, different from the medium, and propagating through it. All other observed alternative models are composed of entity and wave ingredients. However, at the same time they are distinct from each of the constituent models as they have one or more features that are incompatible with both – the entity and wave model. We called these models "hybrid" models and the associated model state - the hybrid model state. Unlike the mixed model state, where the student uses more than one model during the same interview, the hybrid model state is a single model state. We will show how features of these models depend on the context in which the propagation of sound was discussed with the students.

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DEDICATION

I dedicate this work to my family

CHAPTER I

PROBLEM DEFINITION

1.1 Introduction – integration of research

Students come into the classroom with preconceptions about how the world works (Bransford, Brown, & Cocking, 1999). It is claimed that engaging the preconceptions during the teaching practice is necessary to grasp new concepts, which requires that teachers are prepared to draw out their students' existing understanding and help to shape it into scientifically accepted knowledge (Bransford et al., 1999; Donovan, Bransford, & Pellegrino, 1999). For these reasons instruction in physics should focus on students intuitive perceptions about the world, which means that such perceptions have to be identified (Dykstra, Boyle, & Monarch, 1992).

Among a many different types of students difficulties, of special interest for physics education are those, which originate from some structured cognitive concept or mental model. "The term mental model is frequently used today in science education research to describe the way students understand various scientific concepts and ideas" (Zollman & collaborators, 1999). Mental models may contain contradictory elements (Redish, 1994) and are generally different from scientific models. Spontaneous concepts that result from these mental models are today commonly called alternative conceptions (Wandersee, Mintzes, & Novak, 1994). We will address these terms later in greater detail.

During the teaching process we want, in a sense, to "replace" spontaneous mental models with scientific models, which are accepted as valid if they are coherent, stable and experimentally approved. Being familiar with the common mental models and related alternative conceptions, a physics instructor can much more effectively lead the class discussion, particularly before and after an experiment.

Recently, an analytical method for analyzing students' understanding of scientific models was developed by Bao (1999). This method enables quantitative analysis of students' mental models in "real time" (during the lecture or research). To utilize this tool, a model analysis inventory for particular science areas must be constructed, and this research is part of the process of their construction for different physics topics.

1.2. Model analysis

As stated earlier, the model analysis is an analytical method for analyzing students' understanding of scientific models (Bao, 1999; Bao & Redish, 2001; Bao, Zollman, Hogg, & Redish, 2000). It is based on observation that when the learning of a particular physics topic is explored through the systematic qualitative research, usually a small, finite set of commonly recognized models is identified (Marton, 1986). Previous research also shows that students often do not recognize relevant conditions in which to appropriately use their mental models (Bao & Redish, 2001). Consequently, student can use multiple models inconsistently while treating the problems that an expert would consider equivalent. The model analysis gives the information about ability of individual students and the classroom as a whole to correctly apply the relevant concept. We also come to understand how this application varies as the context is changed and what contexts are difficult for students (Zollman & collaborators, 1999).

This approach "assumes that the most commonly used mental models are identified through the extensive qualitative research. These known factors can then be mapped onto the choices of an appropriately designed multiple-choice test" (Bao & Redish, 2001, p.3). This test is called mental model inventory. The results it provides give the explicit information about the students' state of understanding. Finally, computers and software specially designed for particular inventory are used to get immediate feedback in real time teaching. This is the crucial point for educational application of the method.

1.2.1. Mixed mental model state

According to Bao and Redish (2001) one should keep in mind that "the mental states of the individual students tend to be mixed, especially when they are making a transition from an initial state, dominated by naive incorrect model to an expert state" (Bao & Redish, 2001, p.3). Inconsistent responses are interpreted as a measure of the degree to which the student's model state is mixed. The mental models that students use are understood in terms of their own internal consistencies, and not in terms of their position when compared to the experts' view.

It is well documented that in introductory college physics, students frequently use a variety of mental models to deal with questions that are equivalent from an expert's point. Bao and Redish (2001) define that "if a student always uses a particular mental model in a reasonably coherent way in response to a set of expert-equivalent questions we say they are in a pure model state. If the student uses a mixture of distinct mental models in response to the set of questions we say the student is in a mixed model state." (Bao & Redish, 2001, p.8) According to these authors, a student in mixed model state simultaneously occupies a number of different models with different probabilities. Applied over the period of time, model analysis traces the change of model from the old one, through the mixed state, to a new one.

1.2.2. Null model

In the model analysis Bao and Redish (2001) employ also a so-called "null model". It serves to make sure that possible less common, irrelevant and/or not identified models are also included into the analysis. "With the null model included, the set of models becomes a complete set, i.e. - any student responses can be categorized" (Bao & Redish, 2001, p.9). Results of model analysis more explicitly show information relevant for improvement of instruction than a score-based analysis. Knowing student's model states and tracing the changes of these states, instructors can more easily identify possible causes of students' difficulties and develop better instruction strategies to address them (Bao & Redish, 2001; Bao et al., 2000; Zollman & collaborators, 1999).

1.2.3. Model analysis inventory creation process

There are several basic steps in creation of the model analysis inventory (Bao & Redish, 2001; Zollman & collaborators, 1999):

1. Common student models are identified and validated in a particular physics domain. If previous research is not enough for this purpose, additional research through in-depth interviews is conducted. As an example, the following models are commonly found in domain of dynamics:
    - Newtonian model - acceleration of the body is proportional to force applied to it (a~F).

- Aristotelian model - velocity of the body is proportional to force applied on it (v~F).
- Impetus model – the body moves until impetus (sort of moving agent) given to it is exhausted.
- Null model - represents irrelevant (marginally present) and/or possibly not identified models.

2. Multiple-choice, inventory questions are designed to track and measure the development of students' models. The effectiveness of the questions is validated through the research.
3. Responses are analyzed simultaneously with the contexts in which they are given. The results obtained this way provide explicit information about the students' understanding.
4. Finally, computers and software specially designed for particular inventory are used to obtain immediate feedback in real time teaching.

In an ongoing, NSF supported research (grant # REC-0087788), these steps will be completed for a variety of introductory physics domains (Zollman & collaborators, 1999). The study described in this thesis however, is the product of research that was conducted as a small segment of this broad research project. As such, this thesis deals with the first step of model analysis inventory creation and investigates the domain of sound propagation.

1.3. Sound - what makes it a worthwhile topic for this research?

Sound as a physics topic is typically glossed over at all levels as a straightforward example of wave phenomena. Although research related to students' difficulties associated with sound is not as abundant as those related to some other physics topics, numerous difficulties in student's understanding of sound have been identified (Barman, Barman, & Miller, 1996; Hrepic, 1998, 2002; Linder, 1987, 1992, 1993; Linder & Erickson, 1989; Maurines, 1992, 1993; Merino, 1998a, 1998b; Wittmann, 1998;

Wittmann, 2001; Wittmann, Steinberg, & Redish, 1999; Wittmann, Steinberg, & Redish, 2002).

Because of sound's virtual omnipresence in our daily life, this situation deserves our attention. Within sound as a topic, we decided to concentrate on its propagation for two reasons. It is the best defined problematic sub domain of sound, and it also promises the most in an attempt to find underlying principles that govern the set of alternative conceptions.

Several studies (Hrepic, 1998, 2002; Linder, 1987, 1992, 1993; Linder & Erickson, 1989; Maurines, 1992, 1993; Wittmann, 1998; Wittmann, 2001; Wittmann et al., 1999; Wittmann et al., 2002) suggest that a naive mental model is associated with sound propagation, and this model is a common denominator for a number of alternative conceptions related to sound. These authors generally refer to it as a "particle model" of sound propagation. In this model sound travels as a particle-like object. Wittmann et al. (2002) also report "particle pulses model" where it seems that translating particles travel in successive pulses. This model is not yet well defined. Since it is claimed that looking to causes of the problem seems to be more promising than looking to the solutions (Wandersee et al., 1994), by probing students' mental models of sound propagation we hope to find the underlying cause for a variety of observed alternative conceptions.

1.4. Research goal

The goal of the broad research project mentioned earlier (Zollman & collaborators, 1999) is to develop tools that will measure and trace students' states of understanding and also changes in those states during instruction (ranging over a period from one class section to several weeks of instruction). Once developed, these tools should provide a real time feedback on instruction and promote research in ongoing classes ranging from small seminars to large lectures (Zollman & collaborators, 1999). The study described in this thesis is a segment of this research project. Its specific problem and research questions are defined below.

1.5. Problem definition

This is a study to determine what models of sound propagation can be drawn from students' reasoning and to probe how these models depend on context.

1.6. Research questions

Main question:

- What models of sound propagation can be drawn from students' reasoning through in-depth interviews?

Sub questions:

- How are models found similar or different with those already reported in the literature?
- How does the context impact student's mental models?
- Do student's mental models change after instruction?

1.7. Problem evaluation – contribution to science education

The tool for analyzing the state of students' understanding and their mental models was recently developed (Bao, 1999). This study is part of the broader research effort that strives to construct model analysis inventories for different topics in physics taught at introductory college level. As a part of this project, this master's thesis research was specifically concerned with the sound propagation as one of those topics. Together with contemporary classroom technology (classroom response system and on-line homework), the constructed model analysis inventories will permit the extraction and quantitative display of effects of instruction on a class's knowledge during the teaching process. This process will allow for instant adjustments in teaching approaches as opposed to ongoing praxis of post-course assessments and adjustments (Zollman & collaborators, 1999).

CHAPTER II

THEORETICAL BACKGROUND OF THE STUDY

2.1. Theoretical and philosophical framework - constructivism

2.1.1. Introduction

Constructivism is an educational philosophy, according to which learners construct knowledge for themselves (Asynchronous Learning Networks, 1998). It differs from the traditional view, that knowledge exists independently of the individual, and that the mind is a "tabula rasa", a blank tablet on which knowledge is to be imprinted.

To the objectivists, "knowledge and truth exist outside the mind of the individual and are therefore objective" (Runes, 1962, p.217). According to this assumption, knowledge is "true" if it corresponds to reality and "false" otherwise (Bodner, Klobuchar, & Geelan, 2001). Constructivist theories on the other hand, are based on the assumption that "knowledge is constructed in the mind of the learner" and it "results from a more or less continual process in which it is both built and continually tested" (Bodner et al., 2001). However, according to the constructivist view, the knowledge we are "allowed" to construct is the only useful knowledge, that which "works" (Bodner et al., 2001). Consequently, knowledge should be judged in terms of its viability, rather than in terms of whether it is true or false. Similarly Polkinghorne (1992) argues that constructivist theories require a shift "from metaphors of correctness to those of utility." Constructivism is not considered another epistemology, or a way of knowing. Rather, it is said to be a way of thinking about knowing. As such, it serves as a reference for building models of teaching, learning and curriculum (Tam, 2000; Tobin & Tippins, 1993).

2.1.2. Forms of constructivism

Many different schools within this theory fall within the same basic assumption about learning (Chen, 2001). The main two are cognitive constructivism and social constructivism. Cognitive constructivism has again two main versions. One is 'mild' (or 'trivial') (Boudourides, 1998) which is based on the work of Piaget (1972). Knowledge is here actively constructed by the learner and is not passively transmitted by the educator.

In the radical constructivism of von Glasersfeld (1990), cognition is considered adaptive in the sense that it is based on the learner's experience and constantly modified by it. Social constructivism is generally attributed to Vygotsky (1978), who challenged Piaget's ideas by stressing the primary role of communication and social life in formation of meaning and cognition. As a result of their complexity, Philips (1995) sees various forms of constructivism spread out along several different dimensions or continua. Two most significant axes or dimensions are "individual psychology versus public discipline" and "humans the creators versus nature the instructor" (Phillips, 1995). According to Phillips (1995), this second dimension is crucial because at a point somewhere along this dimension, one ceases to be a constructivist.

2.1.3. Problems with the constructivist theory

Due to many generally appealing characteristics, constructivism has enormous influence on contemporary science education thought, research and practice (Phillips, 1995), and this trend has lasted for the last few decades. However, the critics of the theory are also abundant (Matthews, 1993; Osborne, 1996) and some urge caution in its adoption (Millar, 1989; Solomon, 1994).

Three main objections are raised to classroom applications of constructivist theories of knowledge (Bodner et al., 2001). Constructivism is being accused that (1) it questions whether a real world actually exists, (2) it prevents us from saying that a student is wrong and (3) that by concentrating on the process of learning it ignores the role of those who influence the learning. Bodner et al. (2001) argue that all these objections can be overcome by incorporating an alternative view of the construction of knowledge proposed by the clinical psychologist George Kelly (1955) into constructivist theories based on the work of Jean Piaget. Even the authors relatively critically oriented toward the constructivist theory admit that "there is a very broad and loose sense in which all of us these days are constructivists" (Phillips, 1995).

2.1.4. Constructivism and ideological perspectives of this research

The premises of constructivism are baselines of philosophical assumptions or ideological perspectives employed in this research. Constructivists view learning as the result of mental construction.

From the constructivists' point of view, mental models can be defined as internal schemes for understanding that are both - the tools with which knowledge is constructed, and the foundation upon which knowledge is constructed (Brandt, 2002). Further, it is the constructivist's view that students learn by fitting new information together with what they already know. This concept links constructivism to this research as we are trying to find out what students "already know" in the domain of sound propagation. This information is necessary because teaching of physics cannot be effective, in general, if a presentation does not take into account students' existing alternative conceptions (Bransford et al., 1999; Donovan et al., 1999). Also, in the constructivists' perception, learning is affected by the context in which learning occurs, and in this research we want to explore if, and in what way(s), students' models depend on the context in which the sound propagates.

2.2. Conceptual framework - mental models

2.2.1. Definition and nature of mental models

Wider studies of mental model definitions show that no consensus exists about the definition of the term mental model and "some definitions of the concept are even contradictory" (Van der Veer, 2000). According to Cañas and Antolí (1998) the main reason for disagreements in the definition of the mental model is that the term has been used by researchers who work in different fields and who focused on its different aspects. According to Van der Veer (2000), although there is no agreement about the exact definition of the concept, in general, "mental model" refers to the internal representations that people form of the environment through their interaction with it.

The notion of the mental model as a "small-scale model" of reality, can be traced to the work of Kenneth Craik (1943) who stated that mental models can be constructed from perception, imagination, or from the comprehension of the discourse.

According to Johnson-Laird (1983), while reasoning, people construct working cognitive representations of phenomena they interact with. They build mental representations by associating the incoming information with their existing knowledge. In this sense, while reasoning, people construct the mental model. With respect to real-world phenomena, mental models are similar in structure but simpler, and they serve to provide explanation (Johnson-Laird, 1983).

Norman (1983) defines the mental model as the mental representation constructed through interaction with the target system and constantly modified throughout this interaction. Following are Norman's general observations related to mental models (Norman, 1983, p.8):

a) Mental models are incomplete.
b) People's abilities to "run" [employ] their models are severely limited.
c) Mental models are unstable over time (due to forgetting and mixing of old information with new incoming ones).
d) Mental models do not have firm boundaries.
e) Mental models are parsimonious. Users tend to do extra physical actions rather than the mental planning that would allow them to avoid those actions.
f) People often feel uncertain of their own knowledge, even when it is in fact complete and correct (Norman, 1983, p.8).

With a term mental model, Vosniadou (1994) refers to "a special kind of mental representation, an analog representation, which individuals generate during cognitive functioning, and which has the special characteristic that it preserves the structure of the thing it is supposed to represent." Vosniadou (1994) introduces notion of a "synthetic model" which is constructed as a combination of aspects of student's initial model (one based on everyday experience) and culturally accepted, scientific model.

Young (1983) uses the term "user's conceptual model" which is "a more or less definite representation or metaphor that a user adopts to guide his actions and help him interpret the device's behavior" (Young, 1983, p.35). Young states that it is possible to have different mental models about a system, representing different kinds of information.

Minsky in his book *Society of mind* (Minsky, 1986, p.303) writes that: "Jack knows about A means that there is a 'Model' M of A inside Jack's head." For our purpose, this statement is too broad to be considered a useful definition of a mental model. However, his notion of model usefulness is applicable: "Jack considers M to be good model of A to the extent that he finds M useful for answering questions about A" (Minsky, 1986, p.303).

Holland et al. (1989) emphasize dynamic nature of mental models. For these authors mental models are partially based in the static prior knowledge, but “they are themselves transient, dynamic representations of particular unique situations” (Holland et al., 1989, p.14). Therefore, mental models are changed and, most of the times, refined as additional information is acquired.

Through the set of the principles related to mental modes and their implications, Redish (1994) summarizes what he calls a framework for understanding students' learning. His fundamental hypothesis about how the mind works is that people tend to organize their experiences and observation into patterns or mental models.

According to Redish (1994, p.797), mental models have the following properties:

- “They consist of propositions, images, rules of procedure, and statements as to when and how they are to be used.
- They may contain contradictory elements.
- They may be incomplete.
- People may not know how to ‘run’ [employ] the procedures present in their mental models.
- Elements of a mental model do not have firm boundaries. Similar elements may get confused.
- Mental models tend to minimize expenditure of mental energy. People will often do extra physical activities- sometimes very time consuming and difficult-in order to avoid a little bit of serious thinking...
- Students may hold contradictory elements in their minds without being aware that they contradict.” (Redish, 1994, p.797)

diSessa (1996) defines mental models as “frequently instructed knowledge forms that...can be the basis for extended and articulate arguments in the course of developing or displaying explanations or in problem solving” (diSessa, 1996, p. 12). Mental models rely on elaborate and well-developed descriptive components – spatial configurations and causal events.

Witmann et al. (1999) define mental models as patterns of associations (i.e., rules, images, maps, or analogies) used to guide spontaneous reasoning. According to these authors, students' mental models are often incomplete, self-contradictory, and inconsistent with experimental data.

In applying the concept of mental model to human-computer interaction, Van der Veer (2000) "considers mental model any type of mental representation that enables and facilitates the interaction with the system and that develops during the interaction with the system." (Van der Veer, 2000)

Taber (2000) claims that it is possible for a learner to hold several different, yet stable and coherent explanatory schemes that are applied to the same concept area. "This is a significant claim as research evidence that learners apply several different conceptions to a concept area has been interpreted as implying that their thinking is not theory-like, but incoherent, fragmentary and closely context-bound" (Taber, 2000, p.399). This paper argues that, at least in some cases, multiple frameworks are genuine evidence for the manifold of learners' conceptualizations.

Bao and Redish (2001) state they use the term mental model in a broad and inclusive sense and define it as "a robust and coherent knowledge element or strongly associated set of knowledge elements. A mental model may be simple or complex, correct or incorrect, recalled as a whole or generated spontaneously in response to a situation" (Bao & Redish, 2001, p.2).

Brandt (2002) claims that from the constructivists' point of view mental models can be defined as "internal schemes for understanding that are both the tools with which knowledge is constructed and the foundation upon which knowledge is constructed".

According to Johnson-Laird and Byrne (2002) "mental models are representations in the mind of real or imaginary situations…Mental models underlie visual images, but they can also be abstract, representing situations that cannot be visualized". This statement is important for understanding the mental models of sound propagation as we found them in our study.

Greca and Moreira (2002) provide from the physics education research (PER) perspective an operable account: "A mental model is an internal representation, which acts out as a structural analogue of situations or processes. Its role is to account for the individuals' reasoning both when they try to understand discourse and when they try to explain and predict the physical world behavior" (Greca & Moreira, 2002, p. 108). They also state that the understanding of a scientific theory would require the constructions of mental models in the mind of the one who wants to understand it. From Johnson-Laird's work these authors stress his belief that the core of understanding lies in existence of working models in the mind of the individual. Greca and Moreira also state that it seems that students recursively generate mental models based on their initial ones, in attempt to fit into them or to give meaning to the different contents of the subject matter" (Greca & Moreira, 2002, p. 116). These "bifurcated" models that appear as product of this successive reformulation these authors call hybrid models.

Building on his article from 1996, diSessa (2002b) states: "To my mind, mental models should (1) involve a strong, well developed "substrate" knowledge system, such as spatial reasoning, (2) allow explicit hypothetical reasoning, and (3) involve only a small, well defined class of causal inferences" (diSessa, 2002, p.27).

In personal correspondence diSessa (2002a) told me that: "My definition of mental model entails:

1. Strong 'base descriptive vocabulary' - e.g., spatial configuration of identifiable kinds of things.
2. Localized causality - i.e., just a few principles (e.g., 'gears work by conveying motion via contact' or 'resistors work by Ohm's law').
3. Explicit hypothetical reasoning - e.g., 'if this gear moves that way then connected gears move ...'."

2.2.2. Definition of the mental model employed in this study

On the basis of all stated model definitions and characteristics, we decided to distinguish two notions of mental model – a "weak" definition and a "strong" definition. The weak definition is a combination of Greca and Moreira's (2002) definition of mental model and Redish's (1994) list of the properties of mental model.

Therefore we understand a mental model as "an internal representation, which acts out as a structural analogue of situations or processes. Its role is to account for the individuals' reasoning both when they try to understand discourse and when they try to explain and predict the physical world behavior" (Greca & Moreira, 2002, p.108).

Mental models have the following properties (Redish, 1994, p.797).

- They consist of propositions, images, rules of procedure, and statements as to when and how they are to be used.
- They may contain contradictory elements.
- They may be incomplete.
- People may not know how to “run” [employ] the procedures present in their mental models.
- Elements of a mental model do not have firm boundaries. Similar elements may get confused.
- Mental models tend to minimize expenditure of mental energy.
- Students may hold contradictory elements in their minds without being aware that they contradict” (Redish, 1994, p.797).

Also:

- Mental models are dynamic, evolving systems (Holland et al., 1989; Johnson-Laird, 1983; Norman, 1983).
- Mental models underlie visual images, but they can also be abstract, representing situations that cannot be visualized (Johnson-Laird & Byrne, 2002).
- Mental models “bifurcate” (Greca & Moreira, 2002)
- Mental models “synthesize” (Vosniadou, 1994)
- Mental models can be mixed (Bao & Redish, 2001; Taber, 2000; Young, 1983).

Building on the Greca’s (2002) term “hybrid model” we will define hybrid model as a composite mental model that unifies different features of common initial alternative model and scientifically accepted mental model. Hybrid model is at the same time inconsistent (by one or more features) with both models from which it was derived.

We build our strong definition of mental model on diSessa’s (2002a, 2002b) definition. In our strong definition, mental models meet the following (additional) three requirements. Mental models:

1. Involve the strong "base descriptive vocabulary" e.g., spatial configuration of identifiable kinds of things.
2. Involve only a small, well defined class of causal inferences i.e., just a few principles (e.g., "gears work by conveying motion via contact" or "resistors work by Ohm's law".

3. Allow explicit hypothetical reasoning e.g., "if this gear moves that way then the connected gears move ..."."

So, a mental model of the strong kind has (1) spatial configuration of identifiable kinds of things, (2) (few) principles of how system works and (3) (certain) predictive power. While talking about "identifiable kinds of things" diSessa did not restrict them on "correct" things, and neither do we. We also do not restrict mental models to concrete "ingredients" (those that can be visualized) (Johnson-Laird & Byrne, 2002), but recognize abstract ones as valid too, whether they are "correct abstracts" (like the electric field), or incorrect abstracts (like the ether).

2.2.3. Context dependence of mental models

When students' mental models are concerned, we have to note that the different populations of students may have different sets of models. Also, different models are often activated by the presentation of a new situation or problem. Research reveals significant inconsistency of student responses in apparently different situations that an expert would consider equivalent (Clough, 1986; Maloney & Siegler, 1993).

As an example, while analyzing Force Concept Inventory, which is a tool for understanding students' models in dynamics, Schecker and Gerdes (1999) were looking to possible dependence of students' models on context of different questions. In the two different questions students were asked about forces on golf ball and on soccer ball after these have been hit and while they were flying through the air. In the golf ball context, 42 of 87 participants included a force in a direction of motion in their answer. However in the context of the soccer ball, 23 of these 42 students omitted this non-existing force and included in their answers either gravity only, or gravity together with the air resistance. With a similar result in another question, authors concluded that models that students apply are context dependent.

For our study consequently, probing the context dependence of students' models is necessary to determine the limitations and appropriateness of the instrument we intend to build. Different contexts are generally considered apparently different situations that an expert would consider equivalent (and would treat them identically), and which are, at the same time perceived as essentially different by a non-expert. For the purpose of this study, two different contexts can be defined in an alternative, less outcome-based way.

Different contexts are situations that are different enough so there is no single numerical quantity that might relate them to each other. Instead, the difference needs to be conceptually or verbally described.

2.3. Knowledge structures at smaller scale than mental model

Physics education researchers today operate with the variety of mental structures or modes of reasoning (Wittmann, 2001) that are considered more fundamental than the mental model. Of these, we will define here several that are most widely accepted and used.

P-Prims

diSessa (1993) introduced the phenomenological primitive or p-prim, as a hypothetical knowledge structure that often originates as a minimal abstraction of everyday phenomena. P-prims are self-explanatory. They are used as if they need no justification – something happens "because that's the way things are" (diSessa, 1993). "They have predicate logic but this logic is intended only as a familiar example of the reasoning process " (diSessa, 1993, p.116).

Conceptual resources

The concept of the resource as the mental structure was introduced by Hammer (1996; 2000). He defines the resource as "a unit of mind-code" (Hammer, 2002). To explain it, he uses the analogy with a computer program: The resource would be analogous to a sub-routine – one or more functions put together to perform a single useful operation. In some cases the resource and the p-prim can be the same, but Hammer (2000) distinguishes resource from p-prim (phenomenological primitive) as resource does not have to be either phenomenological (can be epistemological, procedural…) or primitive. (In a sense that a resource is not necessarily the smallest meaningful unit, but rather, the smallest practically useful unit of mind processes.)

Alternative conceptions

The term alternative conception refers to "experience-based explanations constructed by a learner to make a range of natural phenomena and objects intelligible" (Wandersee et al., 1994, p.178). As a synonym for alternative conception, many authors today use a new-old term "misconception" (Bao & Redish, 2001; Clerk & Rutherford, 2000), and some also differentiate among them. Example of the latter ones are Abimbola and Baba (1996) who, for the purpose of their study, defined "misconception" as an idea that is clearly in conflict with scientific conceptions and is therefore wrong. They defined alternative conception as an idea which is neither clearly conflicting nor clearly compatible with scientific conceptions but which has its own value and is therefore not necessarily wrong (Abimbola & Baba, 1996).

Wandersee et al. (1994) consider these two terms synonyms, but also suggest the term alternative conception as more appropriate. Clerk and Rutherford (2000) define that "a misconceptions exists if the model constructed by an individual fails to match the model accepted by the mainstream science community in a given situation" (Clerk & Rutherford, 2000, p.704).

While putting the misconception into relation with a mental model, Bao and Redish (2001) define that misconceptions can be viewed as "reasoning involving mental models that have problematic elements for the student's creation of an experts view and that appear in a given population with significant probabilities" (Bao & Redish, 2001). Holding misconceptions theoretically ambiguous, Wittmann (2001) uses term reasoning resources in general fashion to describe any of the smaller grain size modes of reasoning (p-prims, facets of knowledge, intuitive rules, etc). He also distinguishes these from a higher-level concept – a coordination class.

Coordination class

diSessa and Sherin (1998) introduced "coordination class" as the type of concept which is relevant for science education research and teaching. They define it as "systematically connected ways of getting information from the world" (diSessa & Sherin, 1998, p.1171). It is characterized by "an accumulation of a complex and broad set of strategies and understandings" (diSessa & Sherin, 1998, p.1173). So unlike the other mentioned mental constructions, coordination class is a mixture of both – knowledge obtaining strategies and knowledge constructs.

Facets of students' knowledge

In his description of students' knowledge, Minstrell (1992) is defining and cataloging the pieces of knowledge or reasoning that students seem to be applying in problem situations.

He calls these pieces the "facets". We will address this concept later in much more detail as this study contributed to this aspect of knowledge structuring and to corresponding ways of teaching.

2.4. Sound - previous work on difficulties in understanding of sound

In their pioneering work on this subject, Linder and Erickson (1987) identified a number of difficulties that students express in understanding sound. In this early stage, they also realized that students apply different reasoning in different contexts. They conducted a phenomenographic study and interviewed 10 students who completed baccalaureate degree with physics as a major subject and were enrolled in teacher education program. The same authors later (Linder & Erickson, 1989) structured their findings into two qualitatively different ways in which students describe the phenomena of sound:

"The microscopic perspective:

- Sound is an entity that is carried by individual molecules through a medium.
- Sound is an entity that is transferred from one molecule to another through a medium.

The macroscopic perspective:

- Sound is a traveling bounded substance with impetus, usually in the form of the flowing air.
- Sound is a bounded substance in the form of the some traveling pattern" (Linder & Erickson, 1989, p.494,496).

In his review article, Linder (1992) listed observed difficulties in students' understanding of sound:

- "Sound is an entity that is carried by individual molecules as they move through a medium.
- Sound is an entity that is transferred from one molecule to another through a medium.
- Sound is a traveling bounded substance with impetus, usually in the form of the flowing air.

- Sound is a bounded substance in the form of the some traveling pattern.
- Sound is linked to the concept of waves as part of a mathematical physics modeling system (and in this context could not be distinguished from light: the wave equations look identical)" (Linder, 1992, p.258).

In the same paper, Linder proposed several possible reasons for these difficulties:

- Some students seem to be comfortable with conceptualizing the physics in one way and knowing it in another.
- Teachers sometimes use inappropriate analogies (for example, water waves are often used as an analogical example of transverse waves with sinusoidal wave profile).
- Terminology related to sound is often poorly understood by students, and sometimes it is also poorly defined in literature.
- Some common oversimplifications in the topics' presentations in the literature, that have historical roots, may cause problematic understanding.
- Explanations and visual representations in introductory physics textbooks are often misleading (Linder, 1992).

A year later, Linder (1993) identified three qualitatively different ways of describing the sound propagation:

- "Conceptualization No. 1: the speed of sound is a function of the physical obstruction that molecules present to the sound as it navigates its way through a medium" (p.656).

Linder claims that this conceptualization is based on what he calls a sound-resistance factor: "Conceptualized as a physical thing, sound is slowed down by physical obstacles as it travels through a medium" (Linder, 1993, p.656). The two types of the obstacles for propagation are: physical size of the molecules and the density of the molecules in the medium. The resistance is smallest in a vacuum – so speed is the greatest.

- "Conceptualization No. 2: the speed of sound is a function of molecular separation".

Sound is here conceptualized "as an entity which is carried by molecules for a certain distance and then transferred to other ongoing molecules" (Linder, 1993, p.658).

Consequently the speed of the sound is determined by separation of individual sound carrying molecules and therefore it's greater in a denser media.

- ”Conceptualization No. 3: the speed of sound is a function of the compressibility of a medium (the more compressible the medium, the faster the propagation and vice versa)” (Linder, 1993, p.658).

Linder concludes that it seems that all three conceptualizations are result of the students being taught that certain factors (such as density, pressure and temperature) affect the speed of the sound without any explanation how these factors affect it.

Another important contribution to this subject was made by Maurines (1993). He reported results of his preliminary inquiry conducted in the form of conceptual paper and pencil questionnaires that were administered to nearly 600 sixteen-year old French students before any lessons about the sound. Summarized, his findings related to students' understanding of the sound are:

- Sound velocity depends on the source, on the signal amplitude (proportionally) and can decrease with time.
- The medium is the passive support even useless for sound propagation.
- Sound can propagate through the vacuum.
- Propagation is especially difficult when the medium is dense.
- “The supply, a mixture of energy, intensity, speed is given by the source to the medium and is materialized in the ‘sound particle’ ” (Maurines, 1993, p.201).

Comparing these findings with his study about propagation of the visible mechanical signals, Maurines concludes that the same mechanistic rationale observed for the signal on the rope can be seen in the case of sound propagation. The signal is again the material object created and set in motion by the source. The signal is materialized in the “supply” (a mixture of a force, energy and speed) given by the source.

Barman et al. (1996) used sound as a topic to compare two teaching methods – traditional and learning cycle. Thirty-four fifth grade students were randomly selected from a pool of 51 students and assigned to the two treatment groups (learning cycle and textbook/demonstration method). The same instructor taught both classes for the two-week unit. Related to students' understanding of sound, the authors found that:

- Generally, the students viewed sound as an "object" that moved from one place to another.
- Sound can be produced without any material objects.
- Sound is transversal wave that travels similarly like water waves and light waves do.
- When waves interact with solid surface they are being destroyed.

Hrepic (1998) investigated students understanding of sound by using a written survey with open-ended, mostly original questions that covered wide array of sound-related phenomena and situations. He compared results obtained from 8th graders (middle school), high school juniors and college seniors most of which were physics majors. This author concluded that almost all observed alternative conceptions can be found at all of these levels.

The author calls the students' conception that "sound propagates as a particle-like object" the first "law" of spontaneous acoustics. He claims that several other alternative conceptions are consequences of particle conception about propagation of sound. These are:

- Material obstacles slow down propagation of sound.
- If louder, sound travels faster.
- The speed of sound depends on movement of the sound source.
- Sound can be perceived in distance, like a distant object.

Another set of alternative conceptions the author classified as generated by inappropriate knowledge transfer:

- Not all the materials can propagate the sound.
- Electric insulators propagate the sound poorly.
- Sound energy is not generally transformable.

Finally three alternative concepts were claimed to be generated or enforced by school knowledge:

- The denser the medium, the faster sound propagates.
- Speed of sound depends on its frequency.
- Wind influences the frequency of received sound.

In two consecutive articles Merino (1998a; 1998b) presented a set of observations related to common mistaken ideas about sound at the college level. The author derived these observations from personal teaching experience. The first article (Merino, 1998b) deals with the relation of sound loudness and its intensity. Problems he observed related to these are that students often wrongly assume that:

- Intensity and loudness are the same thing.
- Doubling of the intensity of the acoustic wave doubles the acoustic level.
- If a frequency is halved, the corresponding pitch is also halved.
- Regardless of the frequency, a similar acoustic energy always produces the same loudness.
- The timbre of a complex sound is mere overlap of the partials.
- Students are also often not aware of the existence of virtual pitch and the fact that loudness, pitch, and timbre are interdependent properties (Merino, 1998b).

Merino's second article (1998a) deals with concepts of sound pitch and timbre. An understanding of the concept of pitch presents problems since this sensation is commonly linked in a simplistic manner to the fundamental frequency. Although it is the main component in the perception of a tone, the fundamental frequency is not the only one. The tone that we perceive depends also on intensity, on spectral composition, on the duration of the stimulus, on the amplitude envelope and on the presence of other sounds. Also, to perceive the sensation of a tone, the brain needs certain minimal, stimulation threshold time. If the stimulus duration is shorter than this time, the sound is described as a "click" with undefined pitch (Merino, 1998a).

The timbre is a property of the auditory sensation, which allows two sounds of equal loudness and pitch to be distinguished. Therefore, timbre is the subjective correlation of all the properties that do not directly intervene in loudness and pitch (such as its spectral power distribution, temporal envelope and degree of anharmonicity (Merino, 1998a). Merino concludes that any understanding of the nature of sound invariably involves the study of the intrinsic properties of loudness, pitch, and timbre. However, a serious didactic problem in their teaching arises out of the complex structure of those three concepts. A common mistake is identifying the subjective sensory properties, loudness, pitch, and timbre, with the physical magnitudes. Another widespread mistake is association of loudness with wave amplitude only, pitch with frequency only, and timbre with the mere overlapping of two higher partials. Merino suggests that the problem might be solved if teachers improve their knowledge of the three acoustic sensations. Together with practical demonstrations important didactic help is available in the form of instruments (dB-meters, MIDI synthesizers, etc) and software. Beaty (2000) compiled a list of children's misconceptions about science as a result of the AIP Operation Physics Project. The section on sound contains the following list (Beaty, 2000):

1. Loudness and pitch of sounds are confused with each other.
2. You can see and hear a distant event at the same moment.
3. The more mass in a pendulum bob, the faster it swings.
4. Hitting an object harder changes its pitch.
5. In a telephone, actual sounds are carried through the wire rather than electrical pulses.
6. Human voice sounds are produced by a large number of vocal chords.
7. Sound moves faster in air than in solids (air is "thinner" and forms less of a barrier).
8. Sound moves between particles of matter (in empty space) rather than matter.
9. In wind instruments, the instrument itself vibrates not the internal air column.
10. As waves move, matter moves along with them.
11. The pitch of whistles or sirens on moving vehicles is changed by the driver as the vehicle passes.
12. The pitch of a tuning fork will change as it "slows down", (i.e. "runs" out of energy)" (Beaty, 2000)

Wittmann et al. (1999) report on research done in the second semester of a three-semester university physics course at the University of Maryland. In the investigation, a variety of probes were used, including videotaped individual demonstration interviews, pretest (short, ungraded quizzes that accompany tutorials), examination questions, free-response as well as Multiple Choice Multiple Response (MCMR) questions and specially designed diagnostic tests. The authors have found that while describing physics of waves, many students use analogies with Newtonian particle mechanics and related ideas of force, energy, and collisions between the objects. To describe students' difficulties with mechanical waves, the authors organized the data in terms of a mental model. Mental models are here defined as patterns of associations (rules, images, maps, or analogies), used to guide spontaneous answers and reasoning in unfamiliar situations. In their data, the authors see evidence for what they call the "particle pulses mental model" of waves. Analogies that students make using this model are typical for mechanical, particle-physics models (Wittmann et al., 1999). To illustrate students' descriptions of the ways in which the sound waves affect the air, the authors use the metaphor of a "surfer on a wave" where the surfer is a medium pushed by the wave. In accordance with the surfer metaphor, students were often describing sinusoidal waves as a succession of pulses, each exerting a force on particles of the medium and in the direction of wave propagation. Another metaphor that authors used for student's description of the wave propagation was "ball-toss" analogy where the ball was an analogue for a wave.

In his dissertation (Wittmann, 1998), which was the basis for this paper, Wittmann uses the term "particle pulse pattern of associations" and states that it can be loosely referred to as a particle model. In the same research Wittmann also realized that some students understand the wave as propagating air although he did not report this as one of a possible mental models in this domain.

Wittmann (2001) later reported results of reanalysis of his data using diSessa and Sherin's concept of coordination class (diSessa & Sherin, 1998). This approach suggests that students' use of the specific reasoning resources is guided by possibly unconscious clues. Wittmann in this paper defines coordination class as "one of many different possible types of concepts, in which nets of simple and reasonable pieces of information are chosen and linked together" (Wittmann, 2001). The author also uses the term "reasoning resources" broadly to describe any of the smaller grain size modes of reasoning (p-prims, facets of knowledge, intuitive rules, etc).

By considering students' understanding of the mechanical waves while using the coordination classes as made up of reasoning resources, Wittmann shows that students' associations are primarily built around the concept of a particle and not around a series of events. Students "treat wave pulses as cohesive objects, rather than as extended propagating disturbances of the medium" (Wittmann, 2001). This reasoning strategy Wittmann calls the application of the object coordination class to wave pulses.

In another paper (Wittmann et al., 2002) this group of authors reports on their investigation of how students distinguish between the motion of the wave and the medium through which it travels. The researchers posed two different questions related to sound waves. Some students had to describe the motion of a dust particle sitting motionlessly in front of a previously silent loudspeaker after the speaker was turned on. Others described the motion of a candle flame placed in front of the loudspeaker. More than 25 students were interviewed; over 200 answered the questions in a pretest. 137 students answered these questions in a test that was administered 6 weeks after students completed the instructions on waves.

The findings were:

- While describing the motion of a candle flame and the motion of a dust particle, students generally had the same difficulties
- Although students think about waves both in terms of objects and a series of events, they primarily focus on the object-like properties of the system.
- The great difficulty for most of the students is distinguishing between the propagation of the sound wave and the motion of the medium through which sound travels.
- Traditional lecture instruction with the associated homework problems had little effect on student understanding.
- Tutorial that researchers designed to address this topic showed better results than traditional lecture but the gain was not as large as desired.
- The students seemed to think about sound waves as exerting a force on the medium through which they travel in the direction of sound propagation

"In summary, the students:

- Map object-like properties onto sound waves,
- Treat them as solid and pushing through a medium, and
- Do not correctly interpret the event-like properties that are more appropriate in this setting." (Wittmann et al., 2002)

2.5. Conclusions and implications of previous research for this study

According to constructivists' theory, people ultimately construct their own knowledge (Asynchronous Learning Networks, 1998) and organize their experiences into mental models (Redish, 1994). "Mental model is an internal representation, which serves as a structural analogue of situations or processes and enables individual to explain and predict the physical world behavior" (Greca & Moreira, 2002, p.108). Bao (1999) developed the tool for analyzing students mental models called model analysis, which can be employed after common students models in particular physics topic are identified and model analysis inventories are constructed.

One of the first prerequisites for creation of the model analysis inventory is to determine the prevailing mental models in a targeted student population and to describe those models qualitatively. If previous research is not enough to describe and validate reported students' models, additional study is needed.

Sound is a topic in which students exhibit a series of difficulties (Barman et al., 1996; Beaty, 2000; Hrepic, 1998, 2002; Linder, 1987, 1992, 1993; Linder & Erickson, 1989; Maurines, 1992, 1993; Merino, 1998a, 1998b; Wittmann, 1998; Wittmann et al., 1999; Wittmann et al., 2002). The lack of understanding of sound and its propagation are not appropriately addressed from science educators and researchers (Linder, 1993; Maurines, 1993; Merino, 1998a).

We concluded that in the case of sound, the reported research is not abundant and specific enough to determine possible existing models. However, it indicates that students do express alternative models of propagation of the sound (Hrepic, 1998; Linder, 1993; Maurines, 1993; Wittmann et al., 1999). For this reason, this research investigated students' models of sound propagation.

Previous work also indicates that we can expect that students will apply different models in different contexts (Schecker & Gerdes, 1999; Wittmann et al., 2002). In this study, examining the context dependence of students' mental models was necessary to determine the limitations and appropriateness of the instrument we intend to build.

CHAPTER III

METHODOLOGY

3.1. Introduction: qualitative research – basic premises

"Qualitative research is an inquiry process of understanding based on distinct methodological traditions of inquiry that explore a social or human problem. The researcher builds a complex, holistic picture, analyses words, reports detailed views of informants, and conducts the study in a natural setting." (Creswell, 1998, p.15)

For Erickson (1998), the purpose of qualitative research is to describe events and the meanings of those events for those who participate in them. Qualitative research reports narratively describe occurrences and objects of interest, but also give the range and frequency of observed perspectives (Erickson, 1998).

Krathwohl (1998) considers qualitative methods "particularly useful in understanding how individuals understand their world, in showing how individuals' perceptions and intentions in situation determine their behavior, in exploring phenomena to find explanations, and in providing concrete and detailed illustrations of phenomena." (Krathwohl, 1998, p.225). Consequently, qualitative methodology is appropriate for this research as we want to:

- Understand how individuals understand their world in a specific domain –sound propagation.
- Understand how individuals' perceptions depend on the situation.
- Explore phenomena to provide its concrete and detailed illustration.

3.1.1. Qualitative research tools

Qualitative research methods utilize a variety of data collection types, each of which has specific advantages and disadvantages (Creswell, 1994). Most frequently used are interviews, observations, documents and audiovisual materials (Creswell, 1994)

Interviews according to Krathwohl (1998) can be placed along the continuum with increasing amount of structure - unstructured, partially structured, semi-structured, structured and totally structured. Observation is the technique of taking observational notes as a participant or as an observer. Documenting includes variety of possibilities: keeping a journal during the research study, having the informants keep a journal during the research study, collecting the personal letters from informants, analyzing public documents, examining biographies and autobiographies, examining physical evidences and so on. Audiovisual materials are frequently used to record situations of interest and include videotaping social situations, examining photographs and/or videotapes, having informants videotape social situation, collecting sounds (music, child's laughter…) etc. (Creswell, 1994).

This study used several of these methods, with the interview as a primary method. Semi-structured interviews with open-ended questions were the most suitable tool for addressing our research objectives and research questions. Interviews were tape-recorded (audio only), and the students were encouraged to draw on given pictures while explaining their statements.

Of qualitative designs or traditions, this study employed phenomenography.

3.2. Research and analytical framework - phenomenographic research method

3.2.1. Phenomenology

According to Creswell (1998), phenomenology is one of the five major research traditions of qualitative methodologies. It has roots in the philosophical perspectives of German mathematician Edmund Husserl (1859-1938). Etymologically, phenomenology derives its roots from Greek "phainomenon" (phenomenon, appearance) and logos (knowledge, word, reason). Accordingly, phenomenology seeks to understand and to describe the meanings that individual assigns to observed experiences. "Phenomenological data analysis proceeds through the methodology of reduction, the analysis of specific statements and themes, and a search for all possible meanings. In this process researcher needs to set aside all prejudgments, bracketing his or her experiences" (Creswell, 1998, p.52). For phenomenology, the outcome typically consists of a descriptive narrative, a synthesis of knowledge about the phenomena under the study (Creswell, 1994).

3.2.2. Phenomenography

Phenomenography is branch of phenomenology developed by Marton (1978, 1981, 1986). It is primarily interested in describing the phenomenon, as individuals perceive it (graphein in Greek means description). Marton (1978) characterized his approach as a "second-order" or "from-the-inside" perspective that seeks to describe the world as the learner experiences it. He defines phenomenography as the "empirical study of the limited number of qualitatively different ways in which various phenomena in, and aspects of, the world around us are experienced, conceptualized, understood, perceived and apprehended" (Marton, 1994, p.4424).

Phenomenography shares basic theoretical and analytical foundations with its bigger brother phenomenology. The purpose of phenomenography according to Marton is to identify and describe conceptions of reality as faithfully as possible. He states that the more faithful we can be to conceptions we describe, the better we will be able to understand learning, teaching and other kinds of human action (Holden, Balch, & Hockin, 1997).

In phenomenographical analysis, the researcher categorizes data by employing ground rules of internal consistency and of parsimony. The researcher strives to form a minimal number of internally consistent categories, which encompass and explain all the data variations (Hasselgren & Beach, 1996). Marton and Saljo (1984) stress that the categories should emerge from data, whereas in traditional content analysis they would be defined in advance and imposed on the data. However some structure is necessary, and Bogdan and Biklen (1992) suggested considering the topical areas as coding categories. Of possible categories that these authors listed, two are relevant for this study: (1) settings and contexts and (2) perspectives held by subjects. Having established the categories of description, the next step of the phenomenographic research is to find the relationship between them. In this study we sorted obtained information into categories (coding process) with properties of sound as primary way of classification.

A critic of this method, Richardson (1999), states that researchers who employ phenomenograpy should adopt a skeptical attitude toward their interviewees' statements instead of accepting them as a simple truth. Richardson (1999) also critiques the lack of specificity and explicitness that concerns both, the methods for the collection and the analysis of data. Even researchers who embrace the method argue that phenomenography would benefit from a more rigorous consideration of how to engage with the student's life world (Ashworth & Lucas, 2000). In particular, they suggest that more attention should be paid to the processes of empathy and setting aside the presuppositions (bracketing). Saljo (1988) stressed the need for phenomenographic researchers to accept that the categories of description that they put forward were their own constructions, and that other researchers might in principle construct different categories on the basis of precisely the same evidence. Therefore the activities of phenomenographers themselves should not be exempted from phenomenographic analysis. Francis (1993) is critical about generally inadequate reporting of the interview procedures and the interviewees' responses.

Despite these objections, the method became very widely used in science education research during the last two decades and it continues to attract the attention of a number of authors who attempt to improve its theoretical foundation and practical utility (Ashworth & Lucas, 2000). Wandersee et al. (1994) showed the popularity of the approach when they determined that on the sample of 103 researches on alternative conceptions, 46% of them used clinical interviews, 20% used multiple-choice tests, 19% used sorting tasks, 9% used students drawings, 8% used questionnaires, 7% used open-ended tests, and so on. Some of the studies used several methods. Even the critics of the method admit that the approach to qualitative research that Marton and his colleagues developed, "revolutionized the way in which both researchers and teachers think about the process and the outcome of learning in higher education." (Richardson, 1999).

3.3. Procedure

3.3.1. Sampling and sample description

We accomplished our research goal through individual interviews of 26 students enrolled in The Physical World, a concept based introductory physics course at KSU (referred from now on also as P-World). We had several different introductory physics classes as options for this investigation (concept-based, algebra-based and calculus-based classes). At this stage of inquiry we preferred the P-World, as we assumed that its students were less exposed to formal instruction than students of other classes. This factor made the P-World class more suitable for probing the students' initial (spontaneous) understanding of sound propagation. P-World students used *Conceptual Physics* (Hewitt, 1998) as a textbook. Between the pre- and post-instruction interviews they covered the following topics:

1. (Nov. 5th) Vibrations and waves: Speed, Transverse and Longitudinal Waves.
2. (Nov. 7th) Interference, Standing Waves, Doppler Effect.
3. (Nov. 9th) Sound: Origin, Nature, Transmission, Speed.
4. (Nov. 12th) Reflection and Refraction of Sound, Resonance, Interference.

3.3.1.1. Description of interviewed students

Volunteers from P-World were motivated for participation with 20 extra points (2% of total number of points in the class). We had 60 volunteers (38 Female and 22 Male) from class that consisted of 183 students. These volunteers had taken various numbers of physics courses in high school.

Table 3.1

Description of 60 volunteers from the P-World class with respect to their physics background and gender

	No. of High School Physics Semesters	Number of students	Female	Male
	0	28	19	9
	1	6	3	3
	2	25	15	10
	3	1	1	0
Total	-	60	38	22

The majority of students took either none or 2 semesters of physics in high school, and we decided to narrow down the population to these two groups. Of those, we interviewed the students whose time schedule was not in conflict with interviewer's schedule. So sampling and assignment to groups were not random due to several practical issues. The ratio of male and female students was 1:3 (20 females and 7 males), which is somewhat different than the ratio in the class population.

Our sample consisted of 3 different categories:

(a) 16 (sixteen) students, who were interviewed both – before and after the instruction (pre and post-instruction).
(b) 2 (two) students, who were interviewed only before instruction (pre-instruction only).
(c) 6 (six) students, who were interviewed only after instruction (post-instruction only).

Of 18 students interviewed before the instruction, 16 were interviewed also after it. In one case the reason for the dropout was that the student could not find a convenient time for post-instruction interview even after it was rescheduled several times. In another case I mistakenly erased the audio taped conversation of the pre-instruction interview, so post-interview, even if held, would not be useful for determining the model dynamics of this student. Six students were interviewed only post-instruction to see if there is any significant difference in their responses with respect to pre and post instruction interviewed students.

Table 3.2

Description of the sample with respect to number of high school physics classes taken, and gender

	Pre and post interviewed	Only Pre interviewed	Only Post interviewed
No high school physics	**8**	1	2
2 semesters of high school physics	**8**	1	4
Male	**4**	0	3
Female	**12**	2	3
Total number	**16**	2	6

Of the students who were interviewed, the most important for this study were 16 students who were interviewed both, before and after the instruction. From these data we can discuss pre-post instruction model dynamics. We will call this part of the sample the main sample. All others who were interviewed only once, either only before (pre) or only after (post) instruction, will be referred to as – the supplementary sample.

3.3.1.2. Comparison of the sample with the whole P-World class

In this section we compare the interviewed students with the whole P-World class. The bases for the comparison are results that students obtained on the graded exam related to vibrations, waves and sound.

Table 3.3

Comparison of the sample with the rest of the P-World class

	P-WORLD CLASS	Interviewed STUDENTS	Interviewed PRE- and POST-Instruction (ALL)	Interviewed PRE- and POST-instruction WITH NO HS PHYSICS	Interviewed PRE- and POST-instruction WITH 2 semesters of HS PHYSICS	Interviewed ONLY Post-instruction
NUMBER of students that took test	164 (of 183)	22	15	7	8	6
MEAN	54.785	57.188	56	49.286	61.875	50.833
STANDARD DEV.	20.164	23.092	23.391	20.5	25.486	12.007
MEDIAN	55	60	60	55	60	50
MODE	60	60	60	N/A	60	40
MAX	100	100	100	75	100	65
MIN	5	15	15	15	25	40

For easier comparison, first three columns of the table are presented graphically also in the figure 3.1.

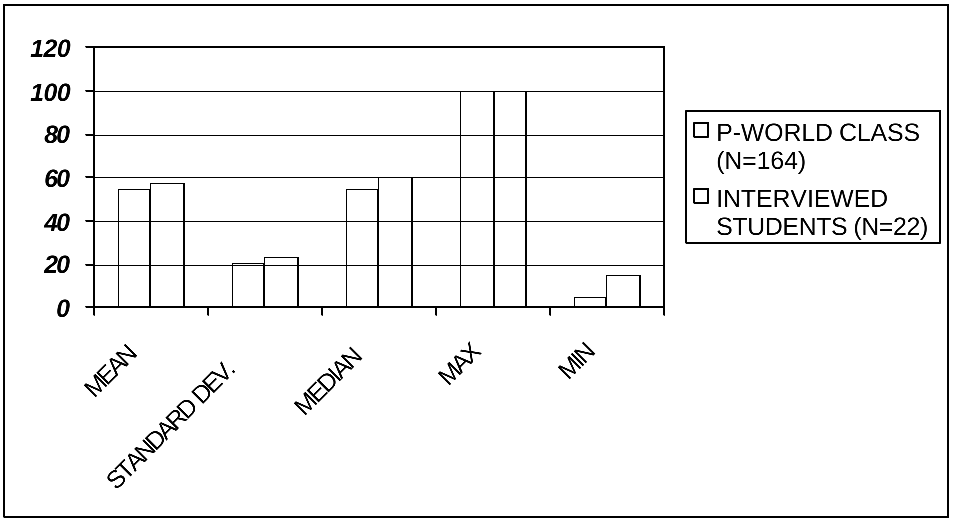

Figure 3.1.Comparison of the interviewed students with the whole P-World class

These data show that according to all relevant indicators, the interviewed students performed on the test either equally well or slightly better than the class. For our purpose it is significant that our sample was not worse. Of those 16 students who were interviewed twice, those with HS physics performed somewhat better than class average and those without HS physics somewhat worse than class in average.

3.3.2. Interview construction

In order to answer the research questions we utilized a semi-structured interview. The interview consisted of the five broad contexts (situations), which an expert would consider rather similar, if not identical. Four of these five broad contexts had two variations, which makes 9 interview contexts in total. A set of questions was associated with each of the contexts. I will use the term interview protocol to refer to all contexts and associated questions.

A relatively big number of contexts was necessary to examine the models from different aspects and to probe for the model stability across the contexts. Also, in this way we attempted to identify possible model triggers e.g. context features that activate a particular model.

Table 3.4

Characteristics of interview contexts

Context	Source	Medium	Receiver/ Detector	Sub-Context characteristics
1.	Voice	Air	Air particles/Ear	Initial, broad question
1a.	Voice	Air	Air particles	Follow up, model targeting questions
2.	Voice	Air	Dust Particle	
3.	Loudspeaker	Air	Dust Particle	Constant tone
3a.	Loudspeaker	Air	Dust Particle	Beating tone with pauses
4.	Voice	Air - Wall - Air	Wall particles/Ear	Macroscopic perspective
4a.	Voice	Air - Wall - Air	Wall particles	Microscopic perspective
5.	Voice	Air - two cans and string	Ear	Air vs. two cans and string
5a.	Voice	Two cans and string	Ear	Tight string vs. loose string

An initial version of the interview protocol was enhanced primarily during the early stage of pre-instruction interviews. The same, early on improved version of the interview protocol was later used in post-instruction interviews. (This protocol is presented in appendix A.)

During the interview, students' had their own copy of the protocol, and they were encouraged to draw on pictures in it. The students' copy consisted of the same set of contexts (called "situations" for clarity) as interviewer's copy. Student's copy also had the same initial explanation of the situations with the first question written in all contexts. Pictures in both copies were also the same. Follow up questions depended on student's answers. Since follow up questions in interviewer's copy of the protocol were possible clues for students' answers (as the distance between us was short enough so they could see my copy), possible follow up questions were written in a non-English language (Croatian).

3.3.3. Research timeline

The study was accomplished through the following steps:

1. We created the semi-structured interview protocol and administered it individually to 18 students attending The Physical World. Students were given no feedback after this interview. This part was finished before class lectures on vibrations and waves began.
2. An interview protocol that was somewhat improved during the first set of interviews was administered after the students finished their lectures on sound. This second interview will be referred to as a post-instruction interview. 16 of 18 initially tested students participated in post-instruction interview.
3. After the instruction, the same interview protocol was also administered to additional 6 The Physical World students who did not participate in the pre-instruction interviewing.
4. After all interviews were finished, participants were given feedback in the form of written explanation of all interview questions. This information was sent to students' e-mail addresses.

In accordance with their lecture time line, we finished pre-instruction interviewing before the first lecture on vibrations (November, 5th, 2001). Post-interview protocol was administered after the last lecture dealing with sound and waves (November, 12th, 2001).

3.3.4. Data collection and organization

After the sample was identified, the same interviewer interviewed all participants individually. The piloted semi-structured interview protocol was prepared and used as the data collection instrument. As the interviewer, I was trying to be not only a concentrated, but also an empathetic listener, and to set aside my presuppositions, as suggested by Ashworth and Lucas (2000). To build the rapport with the participants, before the interview I openly explained to each of them the background of the study and how their participation will contribute to the research goal. Using more than three years of teaching experience, I also tried to establish a non-intimidating atmosphere and non-judgmental attitude to enable and facilitate the openness in the students' answering.

All interviews were audio taped with permission of each subject. Students were encouraged to draw on provided pictures while explaining, so a video camera was not necessary. Although videotaping would have also recorded students' facial gestures and body movements, the intrusiveness of the video camera would not justify its use in this case. Students' drawings were scanned and imbedded into transcripts at appropriate places.

Interviews were in principle transcribed verbatim although some, for research question irrelevant segments, were omitted. In transcript writing we have followed good interviewing and transcribing methods (APA Publication Manual, 2001; Taber, 2000; Wolcott, 1994).

3.3.5. Data analysis

While identifying possible mental models in students' reasoning, we applied standard phenomenographical analytical methods described above. During the coding process we tried to keep maximal closeness to original data. We also ensured that our categories emerged from the data (Marton & Saljo, 1984) and were not imposed on them. One way we ensured reliability was that we did not generalize students' statements over the contexts. So we have identified the model only if all necessary model features existed within the single context. This way we also ensured we were truly probing for context dependence of models and did not mix them over the contexts.

We have sorted obtained information into several categories at different levels of complexity. These categories are:

- Sound properties (lowest level category with the least complex and also with the most numerous constituents).
- Mental models (middle level category).
- Mental model states (highest level category, with the fewest and the most complex constituents).

Mental models were defined in two ways. First, by definition that emerged from subjects' descriptions. Another way was through the sound properties that we identified as uniquely associated with the described models. Since sound properties are simple statements and therefore easy to classify unambiguously, the identified mental models were based on structures far more stable and simple than they are themselves. We also identified the sound properties that are inconsistent with respective models, and made sure none of these inconsistent features appear in the context in which we claimed that the model exists.

So sound properties together with the expressed model definitions were basics for identification of mental models. By relying our complex findings on simple and easy-to-identify ones, we ensured internal consistency (reliability) in mental model identification.

To ensure the validity, we employed two principles. The first deals with the "right model" identification. Of a wide set of sound features that were eligible as unique model identifications, we restricted ourselves only to a few that we have considered perfectly "safe" in a sense that they left no room for ambiguity in interpretation. Also, we made sure that model definitions come from students' statements and are not imposed on them. Secondly, we validated if the identified expressed concept is really a mental model. For this purpose we employed our two-level mental model definition. According to it, some mental models were found as "weak". This means they were possibly provoked by binary-answer type questions or a student stated up front that he/she was guessing his/hers (for model identification relevant) answers. A found model was labeled as "strong" if the model that student described satisfied all requirements we imposed on them in our strong definition of the mental model.

3.3.6. Ethical considerations

Our study was exempted from the full review by institutional review board (IRB), but we anyway decided to comprehensively inform the participants about the research, its background and the purpose. We also asked subjects to sign a consent form. Although no particularly sensitive ethical issues were involved in the study, we have guarantied the anonymity to participants. All of them were asked to give us a nickname that they considered safe in a sense that it does not identify them. These nicknames are used throughout this thesis and all related reports. We also refer to the informants as "he" or "she" according the gender of the nickname that they have chosen. This does not necessarily coincide with their actual gender. The nicknames were used in all quotations and only researchers know the names of participants. The original documents are kept in a safe, locked place and computer data are on a secure server. To protect the anonymity of the instructor, instead of his name, when mentioned, we used: [Instructor].

3.4. Biases and limitations of the study

We differentiate between the potential biases of the study (sources of error for which we were able to compensate to some degree) and the limitations of the study (sources of error for which we could not compensate). Potential biases and their resolutions are listed below so their respective numbers correspond in two lists.

The potential biases of the study are:

1. The sample was not randomly selected. For this reason no conclusions can be made about statistical difference and its possible significance between the interviewed group of students and the class as a whole.
2. Members of the sample were not randomly assigned into groups. Therefore, we cannot determine the impact of the pre-instruction interview on the post-instruction interview although we technically had a control group.
3. The ratio of female to male students in the sample (3:1) was different than in the class population (1.2:1).
4. The P-World class instructor was a member of the research group.
5. I, who conducted and transcribed all interviews, am a non-native English speaker.
6. Determining the model that a student used brings a bias to the classification.

Corresponding resolutions:

1. Official quiz results related to the topic of vibrations and waves showed that we had a population that performed just slightly better than the class average. For our purpose it is significant that it was not worse, as that might open additional questions about limitations. Also, finding the statistical difference is never the aim in phenomenography. What we care about is a descriptive difference.
2. Although six P-World students who were interviewed only after the instruction were not randomly selected and assigned, the results of these interviews allow for logical speculation about the extent of the influence of the first interview on the second one. Generally we assumed that this impact is not significant for our purpose.

3. According to Creswell (1998) a sufficient number of subjects for this type of research is 10 participants. Ideally these subjects would be 5 male and 5 female students, so this study involved more than an “optimal” number of students (5) within each of these groups (we had 20 females and 7 males).
4. The class instructor did not conduct the interviews. He was involved primarily in data analysis and interpretation.
5. The interview protocol allowed for all needed clarifications. Transcripts show that if they existed, misunderstandings were addressed during the interview. While transcribing, I had at my disposal the generous help of several colleagues who are native English speakers. Besides, knowledge of a non-English language helped to ensure that students did not see possible answer clues in my copy of the interview protocol. For this reason it was written mostly in Croatian.
6. Standard reliability checks were conducted throughout the research.

Limitations of the study:

1. The study was held at Kansas State University, a large mid-western public university with essentially open admissions. The site was chosen because of its accessibility, so it was sampled by convenience.
2. Using only P-World students limits our ability to generalize the findings to all students who take introductory college physics.
3. Extra credit offered to participants is a possible source of sample biasing.
4. The interviewer was very familiar with the topic and the previous work on it, which is not an advantage in the case of phenomenographical research.

3.5. Reflection on the process

To gain the understanding of students’ reasoning about sound propagation, in this study we used qualitative methods. The interview we employed was designed to address the research question from the phenomenographical perspective. The same approach was followed in the data analysis procedure. The research timeline was followed fairly linearly. However interviews themselves were more often conducted as loosely controlled dance of student’s statements and a partially pre-defined protocol. The data gathered began to make more and more sense, as the interviews progressed and as the common topics started to emerge. We gradually realized that there are some students' explanations in this topic that seem too abstract for an expert, but that are legitimate and valid justifications from students' perspectives. Altogether, the research was a thought-provoking, challenging and enjoyable experience.

CHAPTER IV

RESULTS

4.1. Difficulties in distinguishing the models - Language degeneracy

One of the first things that we have realized in this study was that while describing sound propagation, students frequently use the same terminology that experts do, and which can be commonly heard from physics lecturers at all levels. However the evidence is that students, while using the terms and expressions in an expert-like manner, don't necessarily have in mind the same things that physicists have, when they use the same words. This situation that the same words and the same expressions have different meanings for experts and novices we have called a language degeneracy.

For example, many students use a variety of statements commonly found in textbooks that describe sound waves (e.g. "Sound waves travel through the air," "Sound is transmitted through the air," "Disturbance travels through the medium," "Vibrations move through the space."). However, these same students commonly make statements inconsistent with wave models (e.g. "sound propagates through the vacuum."). This made the identification of the student's mental models in this area a complex task.

4.2. Models found

In this section I list and define models of sound propagation as they were identified in this study. A major help in addressing the language degeneracy while identifying the mental models of sound propagation was the systematic identification of the properties that students were attributing to sound. We labeled identified sound properties as if they were second part of the sentence beginning with "Sound is…". All identified sound properties are listed in the appendix B and grouped into thematic clusters. In this section we will often refer to them.

We were determining the students' mental models in two ways:

1. Through the definitions that we constructed from students descriptions of sound propagation.
2. Through the sound properties in the cases when we recognized some of them as uniquely associated with the respective model.

Using the above criteria, we identified a dominant alternative model that we call the "entity" model.

4.2.1. Entity model

According to the "entity" model, sound is a self-standing, independent entity different from the medium through which it propagates.

Twelve of 23 subjects expressed the entity model in at least one interview. This model was observed in 5 different contexts (Context numbers: 1a, 2, 3a, 4, 4a).

Together with a model definition, as identification of entity model we have identified four sound properties that we consider uniquely associated with entity mental model. These are:

1. Sound is independent – sound propagates through the vacuum (does not need medium). Example:

   I: Would anything be different for sound in space with and without air?

   ASHLEY: Um…I…don't think so…unless there are things in air that like the sound waves would come in contact with, that would like obstruct where they go, kind of. And then if there…I guess if there's no air then there is nothing for them, nothing to get in the way, so they travel, like free of interference.
2. Sound is material - sound is a material unit, of substance, or has mass. Example:

   I: "Does sound consist of anything material?" (This question was posed after a student stated that sound is independent.)

   VIRGINIA: Yes, I don't know of what, but yes, I am sure it does.
3. Sound passes through the empty spaces between the medium particles (seeping). Example:

   LORAIN: "As the sound moves, like as the sound comes through [the air] I think it might hit…Like it might find the spaces in between the particles [of the air] but, I think eventually it might also hit one. I mean it's not like it knows exactly where it's going."

4. Sound is propagation of sound particles that are different from medium particles. Example:
   STAR: "Well the, the air is what…the sound particles move through. And so in space they don't have any place to move through."

There are two properties of sound that seem to be inconsistent with the entity model but some students' answers indicate they are not. First of these sound properties is "Dependent". According to our definition, sound can be the "entity", and still it may need a medium to propagate (the medium in those cases most often acts as a facilitator – it helps the sound to move). Another property of sound that is not inconsistent with the entity model (as students' answers show) is moving the particles of/in the medium backwards (toward the source of sound). Although the entity model was dominant alternative model of sound propagation, students that had this model regularly were not able to give any description of this entity.

Sometimes in the same interview context, some model-identifying property appeared together with a property contradictory to that model. This situation required either assigning the context to another model or staying noncommittal about the model if two properties were logically self-contradictory. The former case happened only once - when student said in the same context that sound propagates through the vacuum and later that sound may be vibration of the air particles.

Actual excerpts from transcripts that describe the entity model should help reader to get a "feeling" for these models. And in the case of the entity model, also to get a feeling for this "entity". However as these examples are lengthy we added them in the appendix C for all models described by more than one student.

4.2.2. Wave model:

The wave model is the scientifically accepted model. Our operational definitions of the wave model were:

a) Sound is a traveling disturbance of medium particles.

b) Sound is (longitudinal) vibration of medium particles.

Three of 23 informants expressed wave model in 3 different contexts (Context numbers: 1, 1a, 4a).

We considered following sound properties inconsistent with the wave model:

- All entity model identifying properties
- Non-intrusive (for the medium particles and particles floating in the medium - air particles, dust particle, wall particles). Sound does not affect the movement of particles in a direction of a sound propagation.
- Pushing, displacing particles (of the medium particles and particles floating in the medium - air particles, dust particle, wall particles). Sound moves particles of/in the medium in the direction of the sound propagation

4.2.3. Hybrid models

A common feature of all models that we identified besides entity and wave model is that they unify some characteristics of each of these models and form a new, composite model. At the same time, by one or more features, these compound models are inconsistent with both the entity and wave model. This class of composite models we call hybrid models.

The first part of our definition of a hybrid model matches Vosniadou's (1994) definition of what she calls "synthetic models". Synthetic models are "models which combine aspects of the [student's] initial model [one based on everyday experience] and the culturally accepted [scientific] model" (Vosniadou, 1994).

However, the second part of our definition of hybrid model requires that the hybrid model is also inconsistent or incompatible with both the initial and scientific models. This means that those aspects (features) need to be identified in order to define that some model is hybrid.

The term hybrid model Greca and Moreira (2002) use for mental model that appear as consequence of successive reformulation of students' initial model. They call those reformulated models "bifurcated models". So although our definition of hybrid model is in some aspects closer to Vosniadou's (1994) notion of synthetic models, we have chosen to use term "hybrid" as it etymologically better suites our full definition.

4.2.4. Hybrid models expressed by more than one student

4.2.4.1. Shaking model – hybrid

Definition: Sound is a self-standing entity different from the medium. When it propagates through the medium it causes vibration of the particles of the medium (air particles, wall particles) and particles in the medium (dust particles). These particles of/in the medium vibrate on the spot.

Besides the model definition, the following combination of the sound properties is uniquely associated with shaking model: Sound is…

- Intrusive – (particles of/in the medium) vibrate, together with
- Any sound property uniquely associated with the entity model.

This combination identifies the shaking model only if both are expressed in the same context. This is the case also with all other hybrid models that can be identified by some unique combination of sound properties.

Following sound properties are inconsistent with the shaking model: Sound is…

- Non-intrusive (for the medium particles and particles floating in the medium).
- Any movement of the medium particles different than a vibration on the spot.

Two of 23 informants expressed shaking model in 3 different contexts (Context numbers: 1, 1a, 4a).

4.2.4.2. Longitudinally shaking model – hybrid

Longitudinally shaking model is a special case of the shaking model as the type of vibration is here specified as the longitudinal vibration.

Definition: Sound is a self-standing entity different from the medium. When it propagates through the medium it causes longitudinal vibration of the particles of the medium (air, wall particles) and particles in the medium (dust particles). These particles of/in the medium vibrate longitudinally on the spot.

Besides the definition, a particular combination of sound properties identifies the model. Sound is…

- Intrusive – (particles of/in the medium) vibrate longitudinally and
- any sound property uniquely associated with the entity model.

Properties inconsistent with longitudinally shaking model are: Sound is…

- Non-intrusive (for the medium particles and the particles floating in the medium).

- Any movement of the medium particles different than longitudinal vibration on the spot

3 of 23 informants expressed longitudinally shaking model in 2 different contexts (Context numbers: 1, 1a).

4.2.4.3. Propagating air model – hybrid

Definition: Sound propagates so that the air particles travel from the source to the listener.

This definition is at the same time the only identifying property of propagating air model.

Sound properties inconsistent with propagating air model: Sound is…

- Non-Intrusive,
- Intrusive – (particles of/in the medium) vibrate

Overall 2 of 23 informants expressed propagating air model in 4 different contexts (Context numbers: 4, 4a, 5, 5a).

4.2.5. Hybrid models expressed by only one student

Three models presented in this section (4.2.4.) are all hybrid models that were expressed by one student only. Examples of these models are given in appendix C.

4.2.5.1. Vibrating air model – hybrid

Definition: Sound is an entity different from the medium that propagates through the air, which constantly vibrates horizontally back and forth. Vibration of the air particles is identical with and without sound. When the source produces sound, this motion of medium molecules transfers the sound forward.

The sound property uniquely associated with vibrating air model: Sound is…

- Transferred - by vibration of medium molecules that vibrate longitudinally with and without sound.

Inconsistent with vibrating air model is any movement of medium particles different than vibration on the spot. Vibrating air model was expressed by one informant and in 3 different contexts (Context numbers: 3a, 4, 4a).

4.2.5.2. Ether model – hybrid

Definition: Sound is propagation of the disturbance created by longitudinal vibration of ether-like particles that are different from particles of any physical medium. These etheric particles may be called sound, sound waves or sound particles.

Short definition: Longitudinally vibrating particles in space, different from any material medium - are sound (sound waves, sound particles).

Property uniquely associated with ether model: Sound is…

- Moving back and forth – sound (sound wave) moves back and forth

Inconsistent with Ether model: Any movement of medium particles different than vibration on the spot.

Ether and compression model was expressed by one informant and in one context (Context number: 1). Of all models this is the only one that was identified in the weak form (according to weak mental model definition) only.

4.2.5.3. Ether and compression model – hybrid

This model is an upgraded ether- hybrid model. It shares basic features with the ether model but has also several additional features that give it more predictive power.

Definition: Sound is propagation of the disturbance created by longitudinal vibration of etheric particles that are different from particles of any physical medium. These etheric particles are called sound, sound waves and sound particles. To propagate, sound needs compressions and rarefactions of physical medium through which it propagates. However compressions and rarefactions always exist in the medium regardless of sound propagation and sound itself has nothing to do with their formation.

Other implications of this model (as stated by student who described it): Sound is carried by the compressions and rarefactions of the physical medium, and it also travels through them. The speed of sound is different from the speed of compressions and rarefactions, and sound is not the cause of their creation or movement. Compressions and rarefactions do not move relative to each other but along, staying in a phase.

Although sound does not create the compressions and rarefactions in the air, the air is always arranged so that it has some, more or less dense spots, that will serve the purpose and transmit the sound. Solids that sound encounters serve as compressions – spots of higher density. Sound travels faster through compressions than through rarefactions so it travels faster through solids than through gasses. But compressions in air (gasses) can move and fixed solid objects are static compressions. Also, sound diminishes faster while traveling through static compressions (of solids) than through moving compressions (of gases). This explains why sound goes faster though the wall than through the air and yet, it diminishes faster while going through the wall.

Besides the definition, the following combination of properties is uniquely associated with the ether and compression model: Sound is…

- moving back and forth,
- traveling through (the air compressions and rarefactions).

Any movement of medium particles different than vibration on the spot is inconsistent with the ether and compression model.

The ether and compression model was expressed by one informant and in 6 different contexts (Context numbers: 1, 1a, 2, 3, 4, 4a).

4.2.6. Why models identified in this study are hybrid models

In this section I show the features of each of the hybrid models that are coming from wave model and the entity model. I will also explain how each of hybrid models at the same time is inconsistent with both – the entity and wave model.

The shaking model and the longitudinally shaking model have in common with the wave model that while the sound propagates, medium particles vibrate on the spot i.e. they vibrate longitudinally on the spot. This is the same as in the wave model. However, unlike in the wave model, the sound in these hybrid models is a self-standing entity different from the medium. This feature of these models is inherited from the entity model. A feature that makes these models inconsistent with the entity model is the vibration of the medium particles on the spot. In the case of the entity model, medium particles may not be affected at all by sound propagation, but if they are, they move away from it's original position in any direction.

The propagating air – hybrid model is in a sense the entity model in which this entity becomes air particle or more generally – a medium particle. So medium is in a sense a carrier of the sound - which is the feature of wave model. This same feature makes the propagating air model inconsistent with the entity model, as entity is something different from the medium or medium particles. This model is inconsistent also with wave model because in wave model medium particles do not travel from the source of the sound to the receiver.

In the vibrating air – hybrid model sound is a self-standing entity that moves through a medium that vibrates longitudinally all the time, whether the sound propagates or not (unlike with the wave model). So sound is an entity (which is uniquely the entity model feature – inconsistent with wave model) and the medium vibrates longitudinally as sound propagates (uniquely wave model feature – inconsistent with the entity model).

In the ether and the ether and compression models - Sound propagation is (or is enabled by) a longitudinal vibration of etheric particles that are different from particles of any physical medium. So medium itself consists of entities that are equivalent to those of the entity model (the input feature of the entity model - inconsistent with wave model), but they vibrate as medium does in a wave model (the input feature of wave model - inconsistent with the entity model). This vibration of "entity medium" is also inconsistent with the entity model.

Specifically, additional input of wave model to the ether and compression model is that sound needs compressions and rarefactions of a real, actual medium to propagate. However, according to this model compressions and rarefactions exist always in the medium, and sound itself has nothing to do with their formation/creation, which is inconsistent with wave model.

In both, ether and ether and compression models, these etheric particles are called sound, sound waves and sound particles.

4.3. Model distribution and dynamics

4.3.1. Model instruction dependence - consistency and change between pre- and post-instruction interview

In this section we show the distribution of the models found within our main sample. Following are explanations of labels used in the tables that represent observed model distribution.

- Column titled "No." notes student's unique number in this research (which is the same for each student in all tables). The numbers assigned to main sample students correspond to order in which they were post-instruction interviewed.

- “H.S. Physics” stands for - Number of semesters of physics classes taken in high school.
- The model(s) that each student had are shown in the “Model” column. Below is the list of abbreviations used for the models:
    - o Entity model (Abbreviation: E).
    - o Wave model: (Abbreviation: W).
    - o Shaking model – hybrid (Abbreviation: SH).
    - o Longitudinally shaking model – hybrid (Abbreviation: LSH).
    - o Propagating air model – hybrid (Abbreviation: PAH).
    - o Vibrating air model – hybrid (Abbreviation: VAH).
    - o Ether model – hybrid (Abbreviation: EH).
    - o Ether and compression model – hybrid (Abbreviation: ECH).
- When it was not possible to identify which model a student had, in a “Model” column we noted – “No distinct M”, which stands for “no distinct model found”.
- Letters S and W within the parentheses next to a model abbreviation note whether the model was found in a strong (S) or in a weak form (W), according to definitions we stated earlier.
- We could assume that 8 models that we have identified in this study are closed list of models in this domain, and that all students do have a model. In that case we can speculate about the possible models that exist in interviews for which we did not identify the specific model through our data analysis approach. Than, we can ascribe one or two possible models to each of interviews assigned with “no model”. The possible models that we may identify this way are noted in the column “Possible model”.
- Due to restrictions that we have posed on our model identifying features, we were usually able to identify the model only in a few interview contexts (mostly from one to three). In the remaining contexts we were looking for any possible inconsistencies with observed model. If there were such contexts, they were noted in the column “Model inconsistent contexts”.

- Finally, in the last column of these tables, we have stated the sound property or properties that were indicators of identified model and also the context in which the model was identified.

Table 4.1

Model distribution in pre-instruction interview of main population

No.	Nickname	H.S. Physics	Model	Possible model	Model-inconsistent Contexts	Model identifying property of sound (in context)
1.	Hope	0	PAH (S)		None	Definition (4a,5,5a)
2.	Juan Paco	0	No distinct M	E	No distinct M	
3.	Virginia	0	E (S)		None	Independent (1a), Material, Definition (2) Seeping, Sound is propagation of sound particles (4a)
4.	Ashley	0	E (S)		None	Independent (1a), Seeping (4), Seeping (4a)
5.	Jewel	0	E (W)		Possibly 4a (self-inconsistent)	Independent (1a)
6.	Sally	0	E (W)		None	Seeping (4a)
7.	Kayla	0	E (W)		None	Independent (1a)
8.	Jennifer	0	No distinct M	E	No distinct M	/
9.	Jordan	2	SH (S), E (S)		Models mutually inconsistent	Through combination of properties: Intrusive – (air particles) vibrate, Entity-Independent (1), Seeping (4), Seeping (4a)
10.	Donnelizer	2	E (S)		None	Independent (1a), Seeping (4a)
11.	Star	2	E (S)		None	Sound is propagation of sound particles (1a), Material (3a), Seeping (4a)
12.	James	2	E (W)		None	Independent (1a)
13.	Bic	2	E (S)		None	By definition, Material (1a)
14.	Meg	2	No distinct M	E	No distinct M	/
15.	David	2	No distinct M	E	No distinct M	/
16.	Tara	2	No distinct M	E	No distinct M	/

Table 4.2

Model distribution in post-instruction interview of main population

No.	Nickname	H.S. Physics	Model	Possible model	Model-inconsistent Contexts	Model identifying property of sound (in context)
1.	Hope	0	VAH (S)		None	Definition (3a,4,4a)
2.	Juan Paco	0	No distinct M	E	No distinct M	/
3.	Virginia	0	LSH (S)		None	Through combination of properties: Entity-Independent, Intrusive – (air particles) vibrate longitudinally
4.	Ashley	0	No distinct M	LSH or W	No distinct M	/
5.	Jewel	0	EH (W), FAH (W), W (S)		Models mutually inconsistent	All models identified by their respective definitions
6.	Sally	0	E (W)		None	Independent (1a)
7.	Kayla	0	E (W)		None	Independent (1a)
8.	Jennifer	0	SH (S)		None	Through combination of properties: Intrusive – (air particles) vibrate longitudinally; Entity - By definition
9.	Jordan	2	SH (S)		Possibly C2, C3 and C3a (student could not decide)	Through combination of properties: Intrusive – (air particles) vibrate, Entity-Independent (1a)
10.	Donnelizer	2	E (S)		None	Independent (1a), Independent (2), Seeping (4), Seeping, Material (4a)
11.	Star	2	ECH (S)		None	Definition (1a, 2, 3, 4, 4a)
12.	James	2	No distinct M	LSH or W	No distinct M	/
13.	Bic	2	E (W)		None	Definition (2)
14.	Meg	2	No distinct M	E	No distinct M	/
15.	David	2	No distinct M	E	No distinct M	/
16.	Tara	2	W (S)		None	Definition (1a, 4a)

Table 4.3

Model dependence on instruction - Model change between pre and post-instruction interview of main population

Student No.	Nickname	Class	Semesters of high school physics	Interview	Model	Possible models
1	Hope	P-World	0	PRE	PAH (S)	
1	Hope	P-World	0	POST	VAH (S)	
2	Juan Paco	P-World	0	PRE	No distinct M	E
2	Juan Paco	P-World	0	POST	No distinct M	E
3	Virginia	P-World	0	PRE	E (S)	
3	Virginia	P-World	0	POST	LSH (S)	
4	Ashley	P-World	0	PRE	E (S)	
4	Ashley	P-World	0	POST	No distinct M	LSH or W
5	Jewel	P-World	0	PRE	E (W)	
5	Jewel	P-World	0	POST	EH (W), FAH (W), W (S)	
6	Sally	P-World	0	PRE	E (W)	
6	Sally	P-World	0	POST	E (W)	
7	Kayla	P-World	0	PRE	E (W)	
7	Kayla	P-World	0	POST	E (W)	
8	Jennifer	P-World	0	PRE	No distinct M	E
8	Jennifer	P-World	0	POST	LSH	
9	Jordan	P-World	2	PRE	SH (S), E (S)	
9	Jordan	P-World	2	POST	SH (S)	
10	Donnelizer	P-World	2	PRE	E (S)	
10	Donnelizer	P-World	2	POST	E (S)	
11	Star	P-World	2	PRE	E (S)	
11	Star	P-World	2	POST	ECH (S)	
12	James	P-World	2	PRE	E (W)	
12	James	P-World	2	POST	No distinct M	LSH or W
13	Bic	P-World	2	PRE	E (S)	
13	Bic	P-World	2	POST	E (W)	
14	Meg	P-World	2	PRE	No distinct M	E
14	Meg	P-World	2	POST	No distinct M	E
15	David	P-World	2	PRE	No distinct M	E
15	David	P-World	2	POST	No distinct M	E
16	Tara	P-World	2	PRE	No distinct M	E
16	Tara	P-World	2	POST	W (S)	

In the tables 4.1 and 4.2 we see how models and associated properties were distributed between pre and post-instruction interviews and also among students who did, and did not have high school physics. Table 4.3 is provided for easier tracing of changes between pre- and post-instruction pertaining to particular student.

If instead in a tabular form, we represent this data graphically, we can get visual rendering of model change between pre- and post-instruction interview.

To do that we plotted the models and model combinations that we observed in two vertical lists, each related either to pre- or to post instruction interviews (see figures 4.1. – 4.4.). The box "Hybrid models" in figures 4.1. – 4.4. stands for any of observed hybrid models. The observed mixed states were combinations of either "Entity and Hybrid" or "Hybrid and wave" models. Only one student used the multiple hybrid models in the same interview. However, he also used the wave model in that interview, so his response is classified as a "Hybrid and wave".

The model change in these figures is shown with the arrows. Long arrows represent students whose models were identified both, before and after the instruction. Short arrows stand for a student whose model was identified either only before or only after the instruction. Students whose models were not identified in either interview are not shown in figures 4.1. - .4.3. Their possible models are included in the plot of extrapolated model change in the figure 4.4. In a following figure we begin with actually identified models.

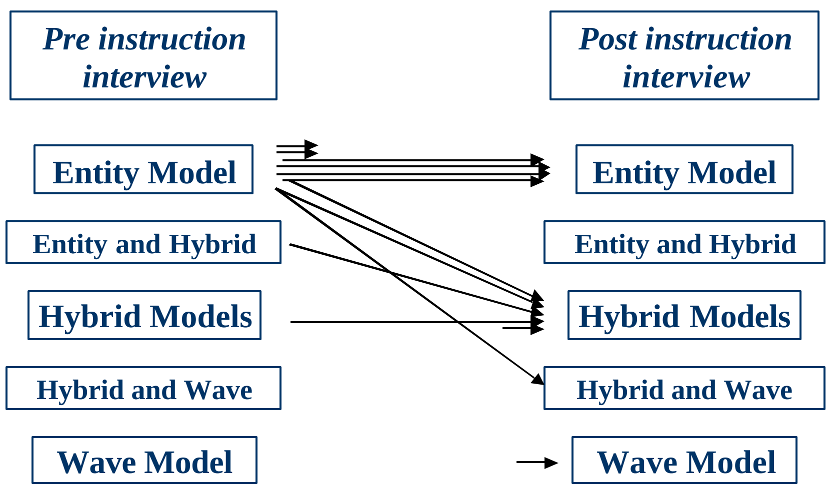

Figure 4.1. Model change between pre- and post-instruction interview of all main sample students.

We can see that there is a clear pattern in this change. Most students start with the entity model and finish either with the same model again or with one of the hybrid models. In the next two graphs we will compare model dynamics of students of main sample that had no HS physics, and those who had 2 semesters of high school physics.

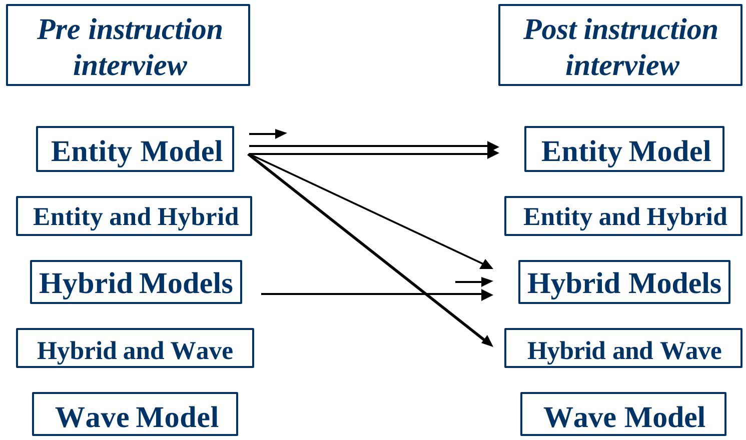

Figure 4.2. Model change between pre- and post-instruction interview of main sample students that had no HS physics.

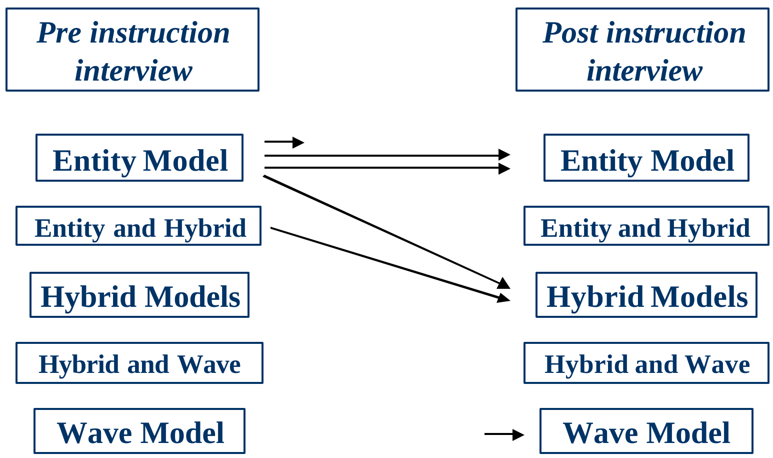

Figure 4.3. Model change between pre- and post-instruction interview of main sample students that had 2 semesters of HS physics.

If we compare figures 4.2. and 4.3. we see that there is no significant difference between these two student groups. Dominant initial and final models are same in both groups.

If we include “possible” or “extrapolated” models, in the way that we assign possible model to each student, we get model dynamics represented in next graphic (Figure 4.4.). Represented data refer to all main sample students. Notice that multiple model boxes are titled here as “Entity and/or Hybrid” and “Hybrid and/or wave” to allow for inclusion of multiple possibilities.

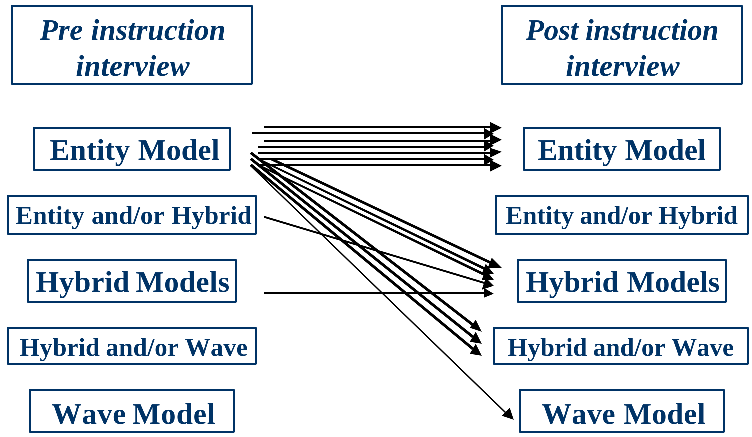

Figure 4.4. Extrapolation of the model change between pre- and post-instruction interview of main sample students.

We see that the Figure 4.4 just reinforces the pattern shown in the Figure 4.1.
A clear pattern is evident in these changes. Students tend to start with the entity model and finish either with the same model or with some of hybrid models. Expanded model analysis just reinforces pattern found for identified models. Almost no difference is apparent in these patterns between students with and without high school physics.

4.3.2. Consistency and change of models during single interview

Of forty interviews analyzed in this study, multiple models were found in only two interviews, which were conducted with two different students. One of these two was Jordan’s pre-instruction interview (student with two semesters of high school physics). In the context 1 of this interview, Jordan expressed the shaking hybrid model by stating that sound was independent entity and that medium particles (air) will vibrate as sound propagates through it.

In the contexts 4a sound was seeping in-between the medium particles (entity identifying property) and Jordan stated that medium (wall) particles will not be affected by sound propagation. So this was “just” the entity model.

In this way, although sound was both times an “entity”, it had different effect on different mediums (air and wall). So it was the context that triggered different models (or we could say - statements that we classified as different models).

Another student who expressed more than one model was Jewel, a student with no high school physics, in her post-instruction interview. Before instruction she expressed the entity model. In the first context of post-instruction interview she had ether model. Throughout later contexts she developed and in context 4a clearly formulated the propagating air model, stating: “The air particle is just gonna continue to go through [the wall] to the listener, causing hearing.” After the last context, while recapitulating her statements, she apparently put things together and associated her earlier ether medium mechanism with the air particle as a sound carrier (associated with propagating air model) and she finished up with wave model.

In both cases the context caused mixed model states. An important question here is why did we observe mixed states in only 2 out of 40 interviews?

A possible explanation is that mental models are not particularly context sensitive in this domain. This conclusion seems straightforward but there are several other possible explanations. It is also possible that our data analysis approach reduced the number of observed mixed model states. To identify the model we required that all necessary model features be stated within a single context. Also we considered several different effects of sound propagation on the particles of/in the medium as being consistent with the entity model. For example, according to our definition, with the entity model a sound may or may not affect the particles of/in the medium through which it propagates. If it does affect them, then according to the entity model it can push them along in the direction of the sound propagation or e.g. it can also disperse them randomly away from the trajectory of sound movement. As I explained earlier, the entity may even push the particles of/in the medium backwards. Possibly these sometimes-large “model bins” together with restrictive analysis approach cut down the number of observed mixed model states.

Finally, since these contexts were presented one after another, possibly students perceived them more similar to each other than they would if the same contexts were presented randomly, mixed with some other, non-related questions or in the different points of time. So perhaps mental models of sound propagation are much more context sensitive than our results suggest at the first glance.

4.3.3. Consistency and change of sound properties (model features) during single interview

We saw that in only two of 40 analyzed interviews, students were in a mixed model state. These two students expressed multiple models due to multiple contexts we presented to them. Thus, if students had a model, they were to a great extent consistent with it across the contexts. In an earlier section (4.3.2.) we explained several possible reasons for weak context dependence of mental models of sound propagation observed in this study. However, different properties that students were attributing to sound were less stable across different contexts.. We have called one of the properties the intrusiveness of sound. It pertains to the movement of particles of/in the medium that is associated with the sound propagation. We were tracing sound intrusiveness across the contexts in all interviews.

If we compare identified models and sound intrusiveness in respective interviews, we can see that they were for the most part consistent with model that particular student expressed, but at the same time they were often not self-consistent. This was possible because of the “large model bins” that we mentioned – our recognition of multiple model features as consistent with particular model.

In the set of tables that follow, we will show students’ consistency related to intrusiveness of sound, i.e. impact of sound propagation on air particles, dust particles and wall particles.

For easier reading of the tables that follow, I will briefly repeat the characteristics of the relevant contexts:

Table 4.4

The characteristics of the contexts relevant for tracing of the intrusiveness of the sound.

Context	**Source**	**Medium**	**Receiver/ Detector**	**Sub-Context characteristics**
1a.	Voice	Air	Air particles	Follow up, model targeting questions
2.	Voice	Air	Dust Particle	
3.	Loudspeaker	Air	Dust Particle	Constant tone
3a.	Loudspeaker	Air	Dust Particle	Beating tone with pauses
4a.	Voice	Air - Wall - Air	Wall particles	Microscopic perspective

Table (4.5) explains abbreviations of observed “outcomes” of sound intrusiveness. These model features are further described in the appendix B.

Table 4.5.

Abbreviations related to intrusiveness of the sound

Abbreviation of movement:	Meaning: The air/dust/wall particle will:
N	• Not move
Y	• Move • Move without specified pattern or direction or pattern of movement. • Move with two different possibilities for direction or pattern of movement.
Y(D)	• Move in the Direction of sound propagation
Y(L)	• Vibrate Longitudinally (back and forth)
Y(L+D)	• Vibrate Longitudinally + move in the direction of sound propagation
Y(T)	• Vibrate Transversally (up and down)
Y(T+D)	• Vibrate Transversally + move in the Direction of sound propagation
Y(S)	• Move Sinusoidally in the direction of sound propagation
Y(V)	• Vibrate; oscillate • Vibrate Longitudinally OR Transversally
Y(L+T)	• Vibrate Longitudinally AND Transversally at same time (circling, spiraling)
Y(DSP)	• Disperse, scatter • Be set into random motion • Be pushed upward/downward
Y (Some of above motions + I)	• Some of motions above with: • Interruptions in motion • Changing amplitude

The movements presented in the tables are those that students stated as their final answer related to specific context. Thus, if student in some later context changed the answer given in a previous context, the later one is listed in the table the answer.

Consistency of movements of air/dust/wall particles

To consider the set of stated particle movements consistent, we set the criteria that the direction of the movement must be included in at least two (out of five) contexts and these have to be the same. If in the remaining three contexts the statement about whether the particle moves or not (simply yes or no) was in accordance with two contexts where student specified the direction of movement, we considered them all consistent. However, if in some of these other three contexts the direction of the particle was stated, then the student was considered self-consistent only if the stated direction of the particle movement was the same in all contexts where it was stated.

For example, if a student says in one context that the particle moves toward the listener and in another that it is affected by sound propagation, we have considered these statements consistent. But if a student says in one context that the particle moves toward the listener and in another that it vibrates, we have considered these statements inconsistent. The following diagram presents findings related to context dependence of sound intrusiveness in pre-interview of the main sample:

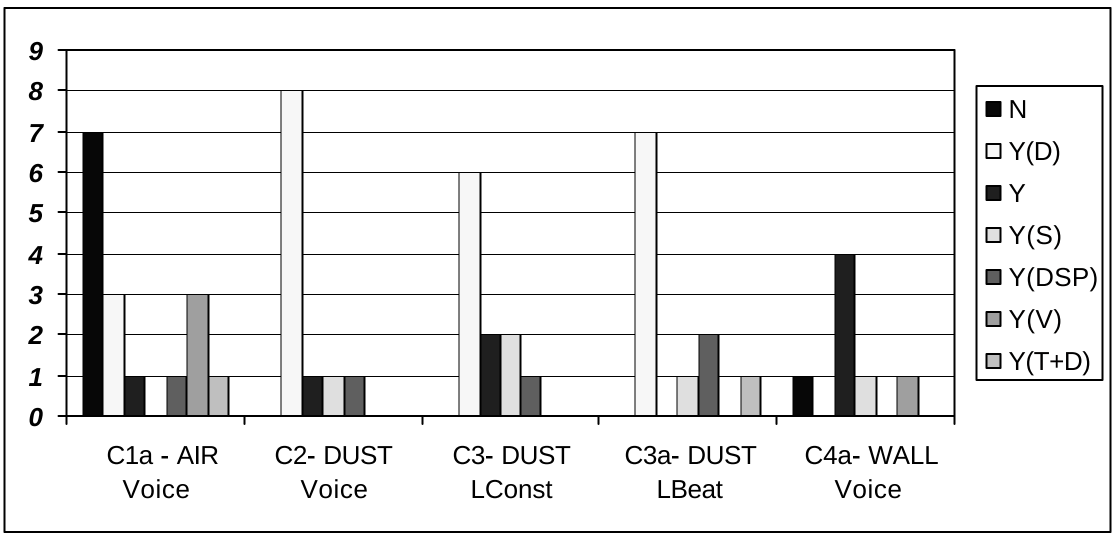

Figure 4.5. Context dependence of sound intrusiveness in pre-instruction interview of the main sample

For each context a single answer is dominant. In the context of air particles, the dominant answer was that sound does not affect the air. In all three contexts related to the dust particle the dominant answer was that the dust particle would be pushed along in the direction of sound propagation. In the case of wall particles the dominant answer was simply – yes, wall particles would be affected but without a defined pattern of movement. The next figure compares how frequent answers about sound intrusiveness were in pre-instruction interview, regardless of context.

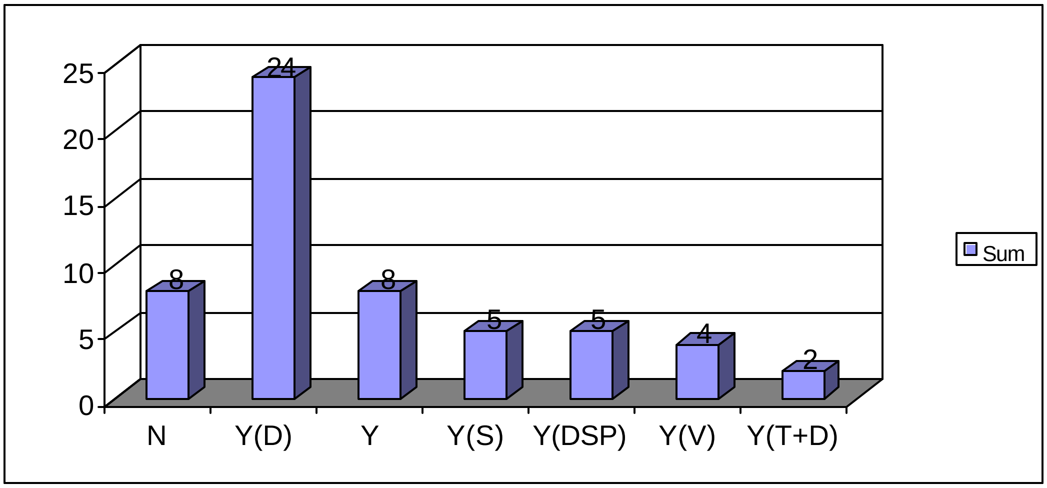

Figure 4.6. Distribution and frequency of anticipated movements of the particles of/in the medium in pre-instruction interview of the main sample

The statement that sound pushes the particles of/in the medium dominate in pre-instruction interview. Longitudinal movement does not appear here at all. The next figure shows how the situation changed in post-instruction interview.

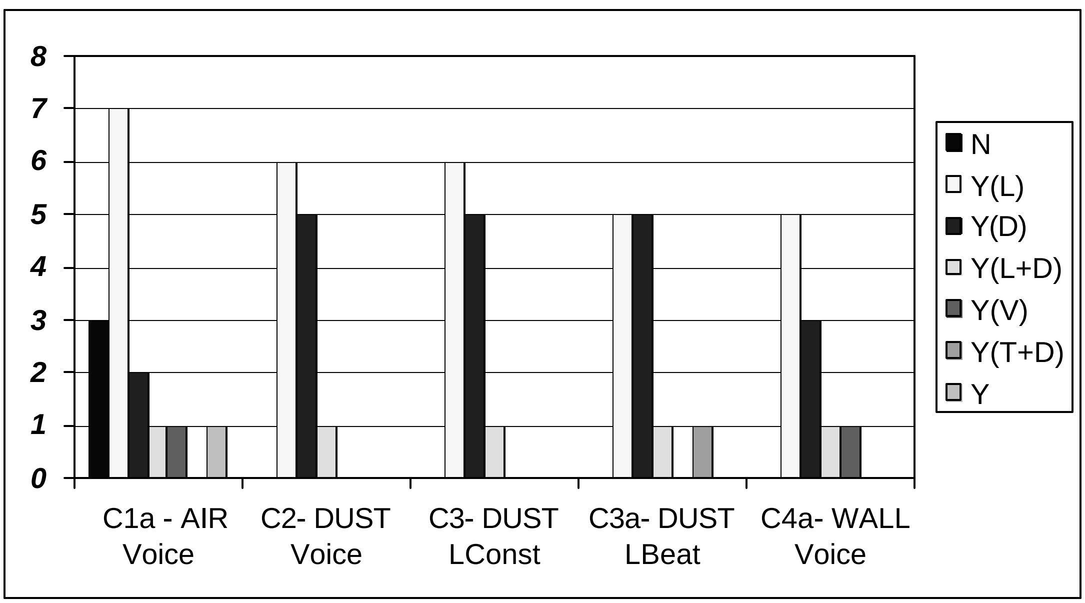

Figure 4.7. Context dependence of sound intrusiveness in post-instruction interview of the main sample

After the instruction, the longitudinal movement was dominant in all contexts although movement of the particles along the direction of sound propagation is also significantly represented. The highest ratio of longitudinal vibration and translational movement we find in the context of air particles. However, in the same context, we also have greatest number of statements that sound does not affect the medium particles. Overall, the greatest difference between pre- and post-instruction situation is that context dependence of sound intrusiveness was significantly reduced in the post-instruction interviews.
The different movements in post instruction interview had following distribution:

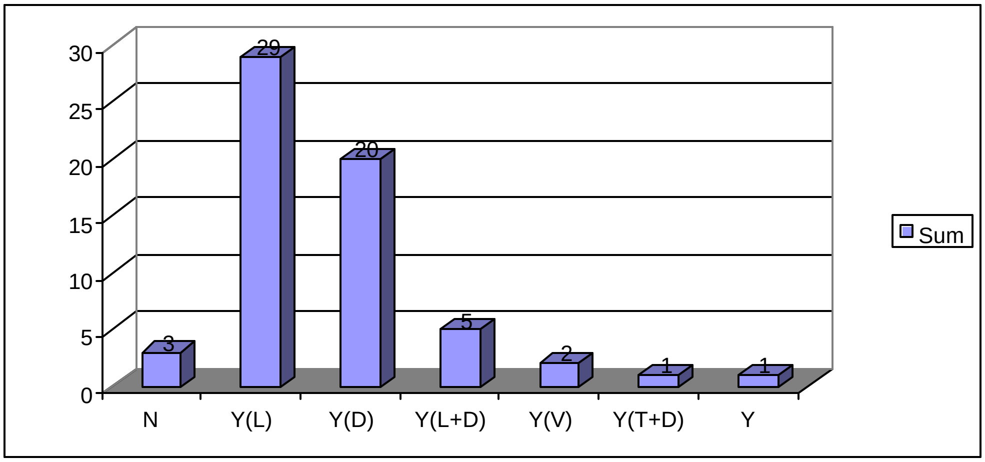

Figure 4.8. Distribution and frequency of anticipated movements of the particles of/in the medium in pre-instruction interview of the main sample

Two movements are associated with sound propagation that were found in post-instruction interview only. These are longitudinal vibration Y(L) and longitudinal vibration with translation Y(L+D). Also, two of movements that were found before instruction disappeared in post-instruction interview: sound disperses particles in random directions Y(DSP) and particles travel along the sine-like curve Y(S). These two were expressed before the instruction in 5 contexts each.

4.4. Supplemental sample findings

In the supplemental part of the sample, we did not find anything significantly different from the main sample. The models we found in the supplemental sample were some of those found in the main sample (the entity model, wave model and two of the hybrid models). We did not find here any model that did not show up in the main sample. The ratio of the number of interviews in which models were found and the number of interviews in which model was not identified was also similar in both populations. The only significant difference between two samples was that among six students who were interviewed only after instruction, three made statements inconsistent with observed model. This type of inconsistency in main sample happened only twice (out of 32 interviews). In one of these two cases, the student could not choose one of two appealing answers, and in another the student expressed two inconsistent model-identifying features within the same context.

Table 4.6. present relevant interview results of supplemental sample in a similar way and using the same abbreviations as earlier.

Table 4.6

Model distribution in supplemental population (students interviewed only once)

Student No.	Nickname	Class	Semesters of high school physics	Number of Interviews	Interview described	Model	Possible model	Contexts not consistent with identified model	Identifying feature (in context)
17.	Mark	P-World	0	1	POST	LSH (S)		C2, C3, C3a	Through combination of properties: Intrusive – (air particles) vibrate longitudinally and (respectively) Entity-Sound is propagation of sound particles (1) Entity-Definition (1a)
18.	Sheila	P-World	0	1	POST	SH (W)		C2, C3, C4a	Through combination of properties:Intrusive – (wall particles) vibrateEntity – By definition (4a)
19.	Mr. T.	P-World	2	1	POST	W (S)		None	Definition (1,1a)
20.	Alley	P-World	2	1	POST	No distinct M	E	No distinct M	/
21.	Jane	P-World	2	1	POST	No distinct M	E	No distinct M	/
22.	Gunz	P-World	2	1	POST	E (S)		C2, C3, C3a, C4a	Independent (1a)
26.	Lorain	P-World	2	1	PRE	E (S)		None	Independent (1a), Seeping (in between air particles) (Recapitulation related to context 1 within context 5)
27.	Ann	P-World	0	1	PRE	Recording erased	Inconclusive	/	/

CHAPTER V

CONCLUSION

5.1. Students' mental models of propagation of sound

In this study we have identified two primary mental models of propagation of sound. These models are:

1. Wave model - scientifically accepted or community consensus model.
2. Entity model - dominant (most frequent) alternative model.

In addition other models were combinations of entity and wave model, and we called them hybrid models.

3. Shaking model – hybrid.
4. Longitudinally shaking model – hybrid.
5. Propagating air model – hybrid.
6. Vibrating air model – hybrid.
7. Ether model – hybrid.
8. Ether and compression model – hybrid.

Of these, three were expressed by more than one student.

So although the number of models is relatively big, a simple pattern relates them. The entity model is dominant alternative model and also most often the "starting point model" in spontaneous reasoning about sound propagation. Another essential model is wave model, which is the community consensus model. All other models (hybrid models), are composites of these two main models as they combine some of the features of entity and wave model.

5.1.1. Identified models and previous research

The particle model and the particle pulses model are alternative mental models of sound propagation described in earlier research reports. The model that we identified as the entity model is in many ways analogous to the particle model. Linder (1992) first used the term "entity" to describe students' notion of the sound as being carried by individual medium molecules and passing from one molecule to another. In a similar way, the “sound particle” was earlier described as the materialization of the supply, a mixture of energy, intensity and speed, given by the source to the medium (Maurines, 1993). We could add to these descriptions that the sound entity, as we observed it, may or may not be material and it may or may not need the medium to propagate. Students may call this sound entity not only a sound particle but also a sound wave, a disturbance or a vibration. The latter of these are scientifically acceptable terms.

Most often, students in our research claimed that the sound is a nonmaterial “entity”, but in their responses it interacts with the medium as if it is a material particle. In that sense it behaves as a photon does. An acoustical analogue of a photon is a phonon. So phonon might be the most appropriate name for the sound entity as we observed. However this would imply that students actually understand this subject at a very high level of expertise, which is far from the truth.

We did not observe the particle pulses model that Wittmann et al. (1999) identified in a case of the constant sound although we had the same context situation. This may be due to different levels of the courses that participants in respective studies attended. Students in that study (Wittmann et al. 1999) were engineering majors and at the time of the study they were taking their second semester of calculus-based introductory college physics course. They associated the sine wave crests with the successive pulses that hit the dust particle floating in the air. However, we did observe something similar in the case of a beating sound i.e. the sound similar to a drum beating with the pauses (context 3a). Usually whatever reasoning a student demonstrated in initial contexts, showed up in the context of beating sound (3a) as a variation of the previous reasoning, but in the on-off sequence. So the reasoning found in our study that we perceive as closest to previously described particle pulses model would be: a beating source sends out successive pulses of sound entities in periods when it produces the sound, and not in silent periods during pauses. Still, although in a sense similar, this is not the same model as particle pulses model of constant sound that Wittmann et al. (1999) described.

Linder (1992) and Wittmann (1998) realized that some students understand a sound wave as propagating air. This understanding we identified as a propagating air model, which is one of the hybrid models that we have identified. Other models and the concept of model hybridizing in this area are some of the contributions of this study. The wave model is the scientifically accepted model and it is not necessary to describe it specifically.

5.2. Mental model dynamics

Sasse (1997) states that detailed knowledge of how users construct, invoke, and adapt mental models could be used to provide guidance to help users to construct the appropriate models. We believe that our findings can contribute in this sense to teaching of sound. In this section we will compare our findings related to the dynamics of mental models with previously reported research results.

As stated earlier, our study indicates that our students expressed only two fundamental models in the domain of sound propagation – a community consensus model and the dominant alternative model. However students showed a lot of inventiveness in fusing these two models into new, hybrid models. This gives new perspective on Marton's (1986) claim that when the learning of a particular physics topic is explored through systematic qualitative research, researchers are often able to identify small, finite set of commonly recognized models.

Wittmann et al. (1999) have found that many students, while answering questions dealing with mechanical waves appear to use a guiding analogy of waves that is reasonably complete and coherent, but not consistent with physical reality. Also, the same study (Wittmann et al., 1999) indicates that many students use elements of many different mental models. This is consistent with our finding that many students do have a model, but it is rarely a simple wave model. It is also consistent with our finding that a variety of non-wave models share multiple features with the wave model. As Wittmann et al. (1999) reported, our study shows that students' answers and models are context sensitive but in our data we also see evidence that students strive to be self-consistent in construction and usage of mental models and model features.

In this study students rarely displayed coherent reasoning at the level of a structured model without being prompted with additional questions, specially in pre-instruction interviews. They were generally expressing (and probably also shaping) their models with the interviewer's additional, model targeting questions. We can see this from the fact that models are rarely found in context 1 (general question about propagation of the speaker's voice without additional model targeting questions), but frequently in context 1a or later. This indicates that some of these models may have been generated on the spot in the students attempt to provide some rationale for the presented situations. So although sound is one of the most common, daily-life phenomenon, students seem unlikely to form a mental model of the phenomenon unless they are "forced" to provide some explanation for the situation.

This finding agrees with notion that people tend to avoid the "wasting" of mental energy (Norman, 1983; Redish, 1994). We don't think about things unless we need to, for some reason.

However, when they attempt to understand and explain the problem, students strive to be self-consistent and to consolidate answers throughout the situations, which they perceive similar enough to do so. This does not agree with Bao's (1999) claim that students generate models randomly. On the other hand, it does agree with Norman's (1983) claim that mental models are parsimonious – students prefer fewer explanations that can explain more problems.

Another finding of this study, which supports some of the previously reported results, is that one of the features of the entity model is that, this "entity" is a highly abstract construction. This supports Smith and diSessa's (1993) claim that novices' intuitive reasoning has many abstract elements.

Reiner et al. (1988) write that naive models of a variety of natural phenomena (electricity, light, heat…) are very often extrapolations of our every day experience with the mechanical world and visible substances (Reiner et al., 1988). He and his colleagues listed a set of different physical phenomena for which naive reasoning seems to be substance based, with substances having the following properties.

1. Substances are pushable (able to push and be pushed)
2. Substances are frictional (experience "drag" when moving in contact with some surface)
3. Substances are containable (able to be contained by something)
4. Substances are consumable (able to be "used up")

5. Substances are locational (have a definite location)
6. Substances are translational (able to move and be moved)
7. Substances are stable (do not spontaneously appear or disappear)
8. Substances can be of a corpuscular nature (have surface and volume)
9. Substances are additive (can be combined to increase mass and volume)
10. Substances are inertial (require a force to accelerate)
11. Substances are gravity sensitive (fall downward when dropped).

As found in this study, all these criteria to different extents apply also to sound and examples for these can be found in the list of sound properties in appendix B.

5.2.1. Context dependence

Our study indicates that generally students consider the reasoning acceptable if they must explain something differently in different situations, but they strive to construct more consistent and more parsimonious explanations if they find it possible. Although models we identified were rarely context dependent, model features change across the contexts much more than models do.

5.2.2. Hybrid models and hybrid model state

Our results also contribute to an understanding of an imperfect mental model view. This view assumes that "self-explaining is the process of revising (and updating) one's own mental model, which is imperfect in some ways" (Chi, 2000, p.196). According to this view, a majority of students do not generate a similar explanation, and each student may have in some ways a unique naive model (Chi, 2000). Greca and Moreira (2002) further state that it seems that "students recursively generate mental models based on their initial ones, in attempt to fit into them or to give meaning to the different contents of the subject matter" (p. 116). Models that appear as products of successive reformulations Greca and Moreira (2002) call hybrid models. These perspectives (Chi, 2000; Greca & Moreira, 2002) do not agree with Bao's (1999) view that "the set of possible models is bounded". Vosniadou (1994) also does not impose any restrictions on the possibility of creation of, what she calls, synthetic models.

Our results support Chi's (2000) and Greca and Moreira's (2002) claims although we did find that certain overall structure in dynamics of model upgrading and repairing exist. This process of improvement of the mental models of sound propagation generally begins with the entity model, which is later upgraded with the features of the wave model. However, this "overall structure" does not limit the number of possible models. The possible outcomes of model restructuring are bounded only by the student's imagination, and in this study this imagination as well as the student's inventiveness in reshaping his/her model (usually to align them with experience), proved very developed.

As stated earlier, building on Greca's (2002) term "hybrid model", and Vosniadu's (1994) notion of synthetic model, we defined a hybrid model as a mental model, which contains the combination of features of the dominant initial alternative model and the scientifically accepted mental model. The hybrid model is at the same time inconsistent (in one or more features) with both models from which it derived. In the case of sound, these essential models are the entity model (initial alternative model) and the wave model (community consensus model). If a student consistently applies a hybrid model across the situations, we say he/she is in a hybrid model state. In our view it is an important special case of the pure model state.

5.2.3. Hybrid model state and mixed model state

If a hybrid model is the only model applied in the interview, and if it is applied in more than one context, we call the associated model state a hybrid model state. Unlike in the hybrid model state, in the mixed model state student applies more than one model. Models combined in the mixed model state can be also one or more hybrid models. So a hybrid model state is a single model state, and mixed state is a multiple model state. This is the reason why a hybrid model state is just a special case of a pure model state.

The last of the possible model states that we need to mention is "No model state" – in which a student incoherently uses different, isolated and incoherent conceptual schemes or resources (in wide sense of that term) to provide explanation of phenomena. This classification is primarily useful in domains of physics where only one dominant alternative model exists. This study indicates that sound is one of those domains. The following diagram represents different model states pictorially. Model features in the figure 5.1. can be any knowledge structure that is simpler or more fundamental than a mental model (e.g. p-prim, conceptual resource, facet of knowledge and so on).

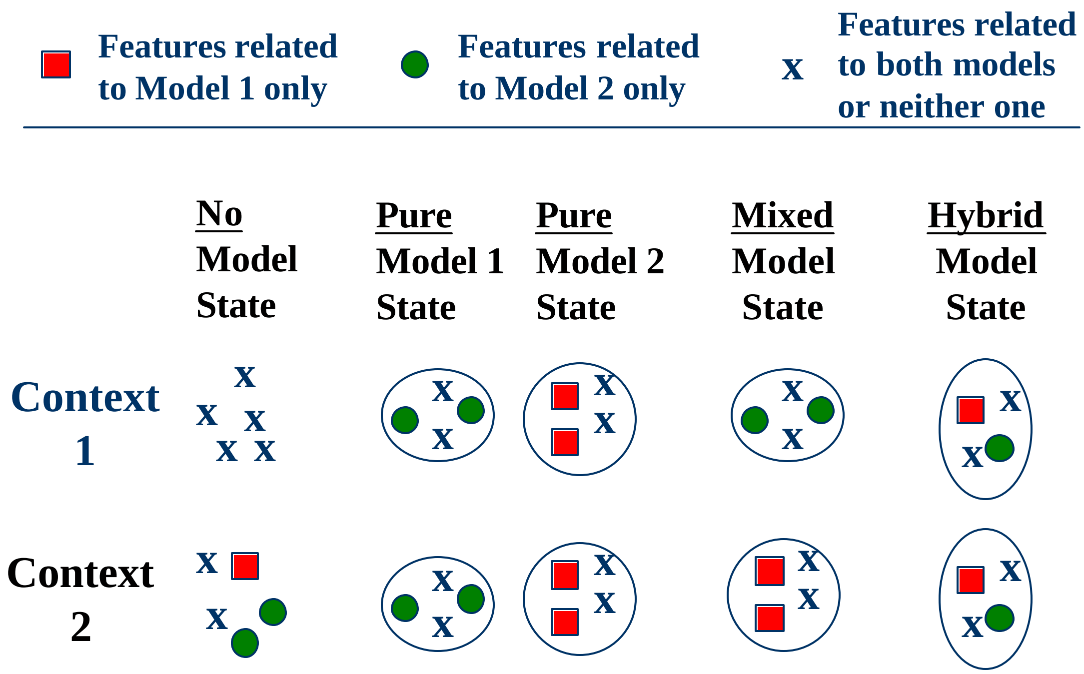

Figure 5.1. Pictorial representation of the different model states

5.2.3.1. Example of Hybrid and mixed model in domain of 2nd Newton's Law

In another, ongoing research Rebello and Itza-Ortiz, (2002), found that some students state that the body moves with constant speed if a force applied on them is constant, and if the force doubles suddenly, the body accelerates with constant acceleration until it reaches twice the original speed. Then, it continues further with constant (doubled) speed. This would be also a hybrid model - a mixture of the dominant alternative model (in this case Aristotelian) and the scientifically accepted model (Newtonian). And if this model is applied consistently in more than one context - that would be the hybrid model state. The mixed model state would be the case when e.g. a student applies reasoning that velocity is proportional to applied force (Aristotelian model) in one context, and in another context that acceleration is proportional to applied force (Newtonian model).

5.3.Implications for Teaching

5.3.1. Hybrid models and the correctness of answers

Although it is certainly not a rule, this study shows that it is possible for student(s) with a hybrid model to have an even better test score than student(s) with the wave model. Of the interviewed students there was only one who had perfect score (100) on the test related to sound. This was Star – a student who in the post-instruction interview used the hybrid model that we called the ether and compression model. Two students that in the post-instruction interviews expressed the wave model had scored 80 and 65 percent respectively. However of all the interviewed students, the two "wave model students" had the two best scores on extra credit part of test, which included some of conceptual questions from our interview protocol.

The conclusion is that, in the case of sound, a student does not necessarily need to have the correct, wave model for a perfect score. Conversely, earning a perfect score does not necessarily mean that the student has the scientifically accepted model.

5.3.2. Sound properties and facets of students' knowledge

As mentioned earlier, in his description of students' knowledge, Minstrell (1992) defines and catalogs the pieces of knowledge or reasoning that students seem to be applying in problem situations. These pieces are called "facets". Minstrell defines a facet as a "convenient unit of thought, a piece of knowledge or a strategy seemingly used by the student in addressing a particular situation" (Minstrell, 1992, p. 112).To describe the facets, a researcher or a teacher uses students' language, in the same way in which they use it to justify their answers, predictions or explanations.

For this reason, the properties that students attributed to sound in this study are at the same time the facets of knowledge. Therefore, we can also refer to the list of properties of sound as a facet list. Identification of facets and their addressing, Minstrell and large number of advocates promote as a promising instructional strategy (2002).

Facet based instruction seeks to utilize the ideas that students bring to class with them. It strives to guide the students through a process of identifying and integrating the productive ideas into their understanding of physics, as well as through the process of weeding out the unproductive ideas (2002). The first step of facet-based instruction is to identify students' preexisting ideas in a physics area, and we believe this study contributed significantly to this step in the domain of sound propagation.

5.4. Suggestions for Further Studies

We suggest that future research on this topic focus on one or more of the following:

1. Probing a similar interview protocol to identify the mental models of sound propagation at algebra and calculus based introductory physics levels.
2. Investigating model development at multiple points along the course of a students' study to deepen the understanding of dynamics of mental model transitions i.e. to understand how and why models change from one to another at the first place.
3. Probing finer grain structure of mental models as p-prims (diSessa, 1988, 1993), resources (Hammer, 2000), and coordination classes (diSessa & Sherin, 1998). By using the term resource in it's broad sense as an unit of the finer model structure we can list several reasons why it might be useful or productive to pay attention to resources while looking to mental models:
   - Transition from alternative to scientifically accepted model might be achieved through the deactivation of the inappropriate resources and activation of the appropriate ones.
   - In the state with no initial model, when concepts are generated on the spot, resources play the dominant or only role in the students' explanations.
     - Students who claim they are "making it up" are frequent. "I'm making it up" can be at least in some cases translated as: "I have no model that helps me so I am pulling out my resources".
     - By pulling out only one familiar resource one can in principle also generate the whole model on the spot (e.g. sound is a signal like a radio wave). Different contexts generally sooner or later bring about the situation when an ad hoc model doesn't work because a prediction based on it contradicts experience. In this case four strategies are possible. The existing model is revised and modified, one moves away from the model to the state of

"resourcefulness", the existing model is changed into another model, and one revises its experience and keeps the model.

- It gives better perspectives for future implementation of findings to instruction than looking to models alone.
- It is possible that some models can be defined through resources.

4. Looking for the ways to resolve existing language problematic that we described as language degeneracy.

5.5. Conclusion

We have investigated students' models of sound propagation and found patterns in their structuring and dynamics. The main result of this research is identification of eight mental models of sound propagation that students' employ, certain insight into dynamics of these models and a list of sound properties or facets of students' knowledge about sound.

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