Students' mental models of sound propagation: Implications for a theory of conceptual change

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Abstract
We investigated introductory physics students' mental models of sound propagation. The study was phenomenographic. In addition to the scientifically accepted wave model, students used the "entity" 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, but at the same time they are distinct from each of the constituent models. We called these models "hybrid" models. We will discuss how students use these models in various contexts before and after instruction and how our findings contribute to the understanding of conceptual change.

Introduction

To help students shape their knowledge into scientifically accepted understanding, we need to identify and address their existing knowledge. According to different theories of conceptual change, during the teaching process we may want to replace existing spontaneous reasoning, to reorganize it or to refine and build on it (Mayer, 2002). Among many different types of students' difficulties, of special interest for physics education are those which originate from some structured cognitive concept or mental model.

According to Van der Veer (2000), no agreement exists about the exact definition of the mental model, but in general, the term refers to the internal representations that people form of the environment through their interaction with it. 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." Our use of the term is consistent with Greca and Moreira (2002, p. 108): "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) Mental models may contain contradictory elements (Redish, 1994) and are generally different from scientific models, which are accepted as valid if they are coherent, stable and experimentally validated.

We perceive a mental model as a mental structure built of more fundamental cognitive and knowledge elements e.g. p-prims (diSessa, 1993; diSessa, 1996) or conceptual resources. (Hammer, 1996; Hammer, 2000) To form a mental model, these elements must be assembled in a coherent way. In this case they become model features or aspects. (Vosniadou, 1994) In the case of sound propagation, which is the topic of this paper, these model features are simply the properties of sound or the qualities that students attribute to sound.

Why sound?

Although sound is an everyday phenomenon that we constantly observe, it is an area in which students display numerous difficulties in understanding. (Barman, Barman, & Miller, 1996; Hrepic, 1998; Zollman, & Rebello, 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) Also, since sound is a wave phenomenon, we believe its understanding is important and contributes significantly to the understanding of both classical and modern physics.

Several studies (Hrepic, 1998, Zollman, & Rebello, 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 reported a "particle pulses model" where students seem to describe the translation of the translating particles traveling in successive pulses.

Within the topical area of sound we decided to concentrate on its propagation because this previous research indicates that a particle-based naive model of sound propagation is an underlying principle responsible for a range of common alternative conceptions found among students at all educational levels.

Context dependence of mental models

Students' mental models may depend on context e.g. (Bao, Zollman, Hogg, & Redish, 2000; Linder, 1987; Schecker & Gerdes, 1999; Wittmann et al., 2002). In other words it is possible for a learner to use several different, yet stable and coherent explanatory schemes (Taber, 2000) when tasks are related to different contextual settings pertaining to the same concept area. Using Bao's (1999) terminology, these students are in a mixed model state. Therefore, we probed students for the context sensitivity of models. This approach was necessary to determine the limitations and appropriateness of the instrument we intended to build. Different contexts are generally considered apparently different situations that an expert would consider equivalent (and would treat identically), and which are perceived as essentially different by a non-expert. For the purpose of this study, two different contexts were 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 described conceptually or verbally.

Research questions

This study attempted to answer following questions:

- What mental models of sound propagation do students use?
- Do students' mental models change with context? If so, how?
- Do students' mental models change after instruction? If so, how?

Context of the study

Our research was conducted through individual interviews of students enrolled in the Physical World, a concept-based introductory physics course at Kansas State University. We had several different introductory physics classes as options for this investigation (concept-, algebra- and calculus-based classes). At this stage of inquiry we preferred the concept-based course, as its students were less likely to be exposed to previous formal instruction about sound than students in other classes. This factor made the conceptual level class more suitable for probing the students' initial (spontaneous) understanding of sound propagation.

The course was taught in a large-enrollment lecture format. The class had a vast diversity in student majors – all of which are non-science. There was an optional lab associated with the course, but it did not include any experiments on the topic of sound.

The class used Conceptual Physics (Hewitt, 1998) as a textbook. Between the pre- and post-instruction interviews they covered the following topics:

1. Vibrations and waves: Speed, Transverse and Longitudinal Waves
2. Interference, Standing Waves, Doppler Effect
3. Sound: Origin, Nature, Transmission, Speed
4. Standing waves, Resonance, Interference

Methods

We interviewed 16 students before and after the instruction about sound. Half of these students had taken two semesters of physics in high school. The other half had no high school physics. Twelve students were female and four were male. These students did not receive any feedback after the first interview. Additionally we have interviewed six students enrolled in the same class only after instruction and one student only before the instruction (the student could not come to post-instruction interview). We refer to the sample of students that we interviewed both before and after instruction as the "main" sample and those that we interviewed once as the "additional" sample. Students received extra credit worth 2% of their total grade for participation in the interviews. On average, our interviewees scored marginally higher than the class mean on the class exam on vibrations, waves and sound. The study was phenomenographic (Marton, 1981, 1986) and we had no hypothesis in the early stage of research.

Interview protocol

We investigated students' mental models in the following contexts using a semi-structured interview protocol:

<u>Context 1, 1a</u>: Propagation of human voice through air without follow-up questions (context 1) and with follow-up questions related to impact of sound propagation on air particles and related to a situation in vacuum (context 1a).

<u>Context 2</u>: Propagation of human voice and its impact on a dust particle in the air.

<u>Context 3, 3a</u>: Propagation of a constant tone (context 3) and a rhythmic, beating tone (context 3a) from a loudspeaker and the impact of these sounds on a dust particle in the air.

<u>Context 4, 4a</u>: Propagation of human voice through a wall at macroscopic (context 4) and microscopic (context 4a) levels and its impact on wall particles.

Context 5, 5a: Students participated in an experiment with propagation of sound through a tight string with cans attached to its ends. We compared propagation of human voice through the tight string vs. air (context 5) and through the tight string vs. the loose string (context 5a).

All situations were represented pictorially. During the interview, students had their own copy of the protocol with a drawing of the situation, a written initial explanation of the situation and the initial question. Students were encouraged to draw pictures while explaining their answers.

Data analysis

During the interview process we realized that while describing sound propagation students frequently use the same terminology that experts do, but often with different meaning or without any meaning. We have found that many students use a variety of statements commonly found in textbooks (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 mechanical wave models (e.g. "sound propagates through the vacuum."). For example, one can find these statements in well known textbooks:

- "In this chapter we shall focus on sound waves that travel through the air and that are audible to the people (Halliday, Resnick, & Walker, 1997, p. 426).
- "Most sounds that we hear are transmitted through the air." (Hewitt, 1998, p.344)

Correspondingly, a student with no high school physics was involved in the following exchange during the pre-instruction interview:

I: *Does air play any role in this process of propagation of sound?*

JEWEL: *I think air plays for the fact that the sound travels through the air and it isn't really doing anything else…it's just wave transmission to the listener's ear.*

We can see that this student, similar to many others, uses the same terminology that experts quoted earlier do. Yet part of the student's statement that "the air…isn't really doing anything else [but being passed through by sound]" indicates that the student's model is not a wave model – the model surely held by textbook authors. Her non-wave model was confirmed a few moments later when the same student stated that in a vacuum sound "echoes" better than in air as there is nothing to absorb it there.

Mental model identification

The observed language ambiguities in students' responses played a major role in our data analysis approach. We determined students' mental models in two ways:

1. Through the definitions that we constructed from students' descriptions of sound propagation, and
2. Through a set of sound properties that can be uniquely associated with the particular model.

Due to language ambiguities, in both of these cases we restricted ourselves to a narrow set of students' statements that could be unambiguously associated with only a model. For example, there was a wide set of properties that students attributed to sound that were eligible as unique model identifications. However, we restricted ourselves only to a few that we have considered perfectly "safe" in the sense that they left no room for ambiguity in interpretation. This was one way we ensured the content validity. We also made sure that model definitions came from students' statements and were not imposed on them. Further, properties that students attributed to sound are in principle very simple statements. For this reason they were easy to classify unambiguously so that the identified mental models were based on knowledge structures far more simple than the models are themselves. Thus, we added to the reliability of the study. We also identified the sound properties that are inconsistent with respective models and assured that none of these inconsistent properties appeared in the context in which we claimed that the model exists.

In order to probe whether students use the same one or different models in various contexts, we identified the model only if a student stated everything that defines a model within the single context. Therefore, we did not combine statements that students expressed in different contexts. In other words we did not generalize students' statements over the contexts.

Findings

Using the above criteria, we have identified, in addition to the scientifically accepted wave model, a dominant alternative model that we call the "entity" model. Other models we have identified seem to be composed of different wave and entity model ingredients. These models we have called hybrid models. In this section we will describe each of these models.

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

Three of 23 informants expressed the wave model in three different contexts (1, 1a, 4a). An example of the wave model - in the words of a student with two semesters of high school physics during post-instruction interview is:

I: *So what is **sound wave**?*

MR.T: *Sound wave **is** um…**nothing more than a** motion, **disturbance in the air, moving in one direction.***

I: *OK. So what is disturbed?*

MR.T: *The position of the **particles**…they don't **move** up and down, just this way **back and forth.***

I: *OK. So does air play a role in this propagation?*

MR.T: *Yes.*

I: *So what's the role of the air?*

MR.T: *The particles of the air, **little molecules that make up the air** make the…**Through the motion they create the wave.***

Entity model

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

Twelve of the 23 subjects expressed the entity model in at least one interview. The model was observed in five different contexts (1a, 2, 3a, 4, 4a).

We have identified four sound properties that we uniquely associate with the entity model. These are:

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

   INTERVIEWER: *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 and has mass. Example:

   INTERVIEWER: *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 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…"*

The sound property that we considered inconsistent with entity model is vibration of particles of/in the medium on the spot that occurs as sound propagates. We have made a list of sound properties that are consistent with the definition of the entity model and considered them inconsistent with the wave model. These include (1) all entity model identifying properties, (2) property of "non-intrusiveness" (sound propagation does not affect the movement of particles in/of the medium) and (3) property of "pushing or displacing particles" (sound moves particles of/in the medium in the direction of the sound propagation).

Hybrid models

A common feature of all models that we identified besides the 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. We call this class of composite models hybrid models.

The first part of our definition of a hybrid model matches Vosniadou's (1994) definition of what she calls a "synthetic model". 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 a hybrid model requires that the hybrid model has a set of features that is incompatible with the students' initial (incorrect) model and another set that is incompatible with the scientific model. This means that each of these sets of features needs to be identified upfront in order to identify some model as hybrid.

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

We will first list and describe three of the hybrid models that were expressed by more than one sudent. These are:

1. Shaking model – Sound is a self-standing entity different from the medium, but as it propagates through the medium it causes vibration of the particles of/in the medium. (expressed by two students and in contexts 1, 1a and 4a)
2. Longitudinally shaking model – This is a special case of the shaking model where propagation of sound-entity causes longitudinal vibration of the particles of/in the medium (expressed by three students and in contexts 1 and 1a)
3. Propagating air model – Sound propagates so that air particles travel from the source to the listener. (expressed by two students and in contexts 4, 4a, 5 and 5a)

There were three other hybrid models that were expressed by only one student each. Their common feature is that they are all more complex than models shared by multiple students. It is this complex nature of uniquely described models that is important for our discussion. For this reason we will describe one of them as an example of this complexity.

Ether and compression model – Sound is propagation of the disturbance created by longitudinal vibrations 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. In other words according to this model, longitudinally vibrating particles in space that are different from any material medium - are sound (sound waves, sound particles). However, in order to propagate, sound needs compressions and rarefactions of the physical medium through which it propagates. Compressions and rarefactions always exist in the medium regardless of sound propagation and sound itself has nothing to do with their formation. The air is always arranged so that it has some more or less dense spots that will serve the purpose (of compressions and rarefactions) and transmit the sound. Solids that sound encounter (like a wall) also serve as compressions – spots of higher density. Sound travels faster through compressions than through rarefactions so it travels faster through solids than through gases. But compressions in air (gases) can move and fixed solid objects are static compressions. Sound diminishes faster while traveling through static compressions (of solids) than through moving compressions (of gases). This explains why sound goes faster through the wall than through the air and yet, it diminishes faster while going through the wall. The student who described this model, used it to explain sound propagation in six different contexts (1, 1a, 2, 3, 4 and 4a).

Pre-post instruction model dynamics

In this section we show the distribution of the students' models and their change observed in the main sample. To represent the model change between pre- and post-instruction interviews we plotted the models and model combinations as shown in figure 1.

The box "Hybrid models" in figure 1. stands for any of the observed hybrid models. When multiple models were identified in the same interview, they were either a combination of entity and some hybrid, or of hybrid and wave models. Each of these combinations is represented by its respective "box" in figure 1. All students who used the hybrid model used only one model, except one student who used multiple hybrid models and the wave model (in the same interview). For this reason, this student, who is in a mixed model state, is classified as "hybrid and wave."

The model change in this figure is shown with the arrows. Long arrows represent students whose models were identified both before and after the instruction. Short arrows stand for students whose model was identified either only before or only after the instruction. For example, if the arrow representing a student starts from the entity model box, that does not mean that he or she stated entity model in all interviews, rather that the entity model was the only one identified in that interview.

Fig. 1 shows the model change of all students in a main sample. From this figure we can see that a pattern exists in pre-post instruction model dynamics. Students generally begin with an entity model and finish either with the same model or somewhere closer to the wave model. Each arrow indicates a single student's model transition.

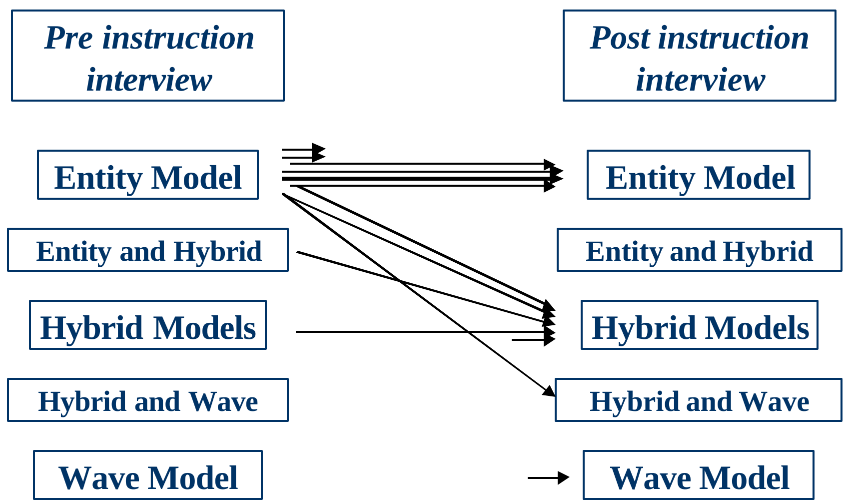

Fig. 1: The change in model states due to instruction.

We have found no difference between students in the main sample that had no high school physics and those who had two semesters of high school physics in terms of pre-post instruction model dynamics. Dominant initial and final models are almost identical in both groups.

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 any model that did not show up in the main sample. The ratio of the number of interviews in which models were identified and in which model was not identified was also similar in both samples.

Use of multiple models

Students used multiple models simultaneously (i.e. they were in a mixed model state) in only two of 39 interviews. This may suggest that mental models of sound are not particularly context sensitive.

However, there are three alternatives to this explanation:

- The contexts were presented one after another and were all dealing with sound propagation. Therefore, students may have perceived them as being more correlated than they would otherwise.
- Our stringent criteria for identifying mental models may have reduced the number of observed models. As we have said, we did not generalize students' statements across the contexts. Instead we identified a mental model only if all necessary statements were expressed within the single context. We did not do so because in that case we would not be probing for the context dependence of the models.
- In some cases we treated several slightly different sound properties as being equivalent with respect to a particular model. For example, we considered a student's description of sound pushing the particles of/in the medium toward the listener to be consistent with the entity model. At the same time we considered some other outcomes of sound propagation on these particles also consistent with entity model, e.g. students' description of sound dispersing those particles randomly away from the trajectory of its propagation.

Validation of identified cognitive structures as mental models

During the analysis process we used Greca and Moreira's definition (2002) of a mental model to identify mental models. After this, to ensure that identified knowledge structures are indeed mental models, we have performed additional checks related to the nature of identified cognitive elements. For this purpose we have used diSessa's (2002) definition because, as far as we know, he imposed the most specific requirements on a mental model as a cognitive structure. These requirements are (a) spatial configuration of identifiable kinds of things, (b) (few) principles of how a system works and (c) (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, an incorrect and abstract concept that physicists developed themselves). The result of using these criteria is that besides being consistent with Greca and Moreira's definition (2002), all identified models except one uniquely stated model (not described in the paper), satisfied diSessa's (2002) requirements. Although in some contexts, identified models were consistent only with Greca and Moreira's definition (2002) and not with diSessa's (2002), this additional criterion validated that knowledge structures that we have described are mental models.

Discussion

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 were a material particle. In that sense it behaves as a photon does. An acoustical analogue of a photon is a phonon. Therefore, one might suggest that the phonon is an appropriate name for the sound entity that we observed. However this conclusion 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 contextual situation. This result may be due to different student levels in respective studies. Students in Wittmann's et al. (1999) study were engineering majors and at the time of the study they were taking their second semester of a 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. We observed something similar in the case of a sound comparable to a beating drum with the pauses (context 3a). Usually whatever reasoning a student demonstrated in initial contexts (related to constant sound or constant speech) showed up in the context of beating sound (3a) as a variation of the previous reasoning, but in the on-off (action – no action) sequence. So the reasoning found in our study that we perceive as closest to the previously described particle pulses model would be: a beating source that 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 model is not identical to the 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. We described this understanding as the propagating air model, one of the hybrid models. Other models and the concept of model hybridizing in this area are some of the contributions of this study.

Mental model dynamics

In this section we 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 a 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 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 pure wave model. In this study a variety of models shared multiple features with the wave model, but at the same time they were also inconsistent with a wave model. Our research, as well as Wittmann's et al. (1999) 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.

Another finding of this study that 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. (Reiner, Chi, & Resnick, 1988; Reiner, Slotta, Chi, & Resnick, 2000) write that naive models of a variety of natural phenomena (electricity, light, heat…) are very often extrapolations of our everyday experience with the mechanical world and visible substances. He and his colleagues listed a set of different physical phenomena for which naive reasoning seems to be substance based. As found in this study, these criteria to a significant extent apply also to sound, in cases when it is understood from the entity model perspective.

Mental model creation and maintenance

In this study students rarely displayed coherent reasoning at the level of a structured model without being prompted with additional questions, especially 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 when additional questions were asked. This result indicates that some of these models may have been generated on the spot in the student's attempt to provide some rationale for the presented situations. So although sound is one of the most common daily-life phenomena, students seem unlikely to form a mental model of the phenomenon unless they are "forced" to provide some explanation for it. This finding agrees with the notion that people tend to avoid the "wasting" of mental energy (Norman, 1983; Redish, 1994). We don't think about things unless we must for some reason.

In several instances, while explaining their answer, students claimed they are "making it up." These students clearly did not have any initial model to work with, so they were generating concepts on the spot. In this situation they "make up" their answers out of their existing cognitive and knowledge elements. Used in this way, these elements represent available cognitive means of handling the situation and can be called "mental resources" (e.g. Hecker, Dutke, & Sedek, 2000) in a generic sense of the word "resource."

If fundamental cognitive elements are assembled in a coherent way, they make up the mental model (Vosniadou, 1994). Therefore, while "making it up" a student can, in principle, generate the mental model on the spot.

However, questions in different contexts generally bring about the situation sooner or later when an ad hoc model doesn't work because a prediction based on it contradicts experience. In this situation, students used four different strategies in our study: (1) the existing model is revised and modified, (2) one moves away from the model to the state of "resourcefulness," (3) the existing model is changed into another model, and (4) one revises its experience and keeps the model.

From these examples we see that mental model dynamics are based on underlying dynamics of more fundamental elements of reasoning. Also, transition from an alternative to a scientifically accepted model might be achieved through the deactivation of the inappropriate elements and activation of the appropriate ones (Hammer, 2000). It is also possible that some models can be defined through conceptual resources that a student uses. Finally, analyzing students' concepts through smaller grain cognitive elements gives an enhanced perspective for future implementation of findings to instruction. For these reasons, we find it useful and productive to pay attention also to more fundamental knowledge elements while looking to mental models.

Mental model context dependence

Our study indicates that using different explanations in different situations is generally an acceptable "technique" for students. However, they strive to construct more consistent and parsimonious explanations if possible. In an attempt to understand and explain the problem, students strive to be self-consistent and consolidate answers throughout the situations, which they perceive similar enough to do so. Our data supports this claim. In 12 instances students changed their previously given answer related to some earlier discussed context. Of these twelve, 11 were related to the effect of sound propagation on particles of/in the medium ("intrusiveness" of the sound). In each of these cases, when an answer was changed, the new answer improved the overall self-consistency of the student's answers. A twelfth change, one not related to sound intrusiveness, was neutral with respect to self-consistency. This finding agrees with Norman's (1983) claim that mental models are parsimonious – students prefer fewer explanations that can explain more problems. Although the situation in an interview setting may be different in this respect from e.g. multiple-choice testing, we would not say it is accurate to claim that students generate models randomly in different contexts (Bao, 1999). Not at least in a probabilistic sense of the term "random".

In our study, students rarely used different models in different contexts, i.e. identified models were rarely context dependent. However, the features or aspects of these models (Vosniadou, 1994) were changing across the contexts significantly. As an example, there were four students who used the entity model in air context as well as in the wall context during the same interview. Three of these students stated that during sound propagation air particles are pushed away from the source but the motion of wall particles is unaffected. A fourth student, on the other hand stated exactly the opposite. Yet the model was the same in all of these cases and respective contexts. In other words, because a student assigned a different property to sound in different contexts, it does not necessarily mean that a student uses a different model. However, if a student uses different models, sets of related properties will be different.

Even though model aspects change across the contexts notably and much more than models do, in our opinion this is still in agreement with our claim that students endeavor to be self-consistent. To illustrate this claim, we ask a reader to consider for a moment our experience with a flying ball and its interaction with objects in its way. Although we may have a very clear picture of ball propagation in mind , its shape, mass and velocity, our answers will be different if we are asked about the outcome of an interaction of this ball with a window glass, concrete wall or tree branch. In the same way, a student may have exactly the same model, yet give very different answers when asked about dynamics of particles of/in the different mediums.

Model states

As we said earlier a mental model is a mental structure built of more fundamental cognitive and knowledge elements that, when assembled into a mental model, become mental model features (Vosniadou, 1994). A student's mental model state (Bao, 1999) is defined by the mental model(s) that the student uses across different contexts.

Figure 2 depicts various model states and their relationship with knowledge elements i.e. model features. Students who use disconnected knowledge elements are in a "no model" state. Students in a "pure model" state construct a model by connecting features pertinent to this model and applying the model consistently across various contexts. Students in a "mixed model" state use two or more mental models. In each context, they apply one of these models. Students in a "hybrid model" state construct a single model from features associated with different models. In hybrid model state they apply a respective hybrid model consistently across various contexts. This makes a hybrid model state a special case of a pure model state that is very important for understanding the conceptual change in various domains (Vosniadou, 1994).

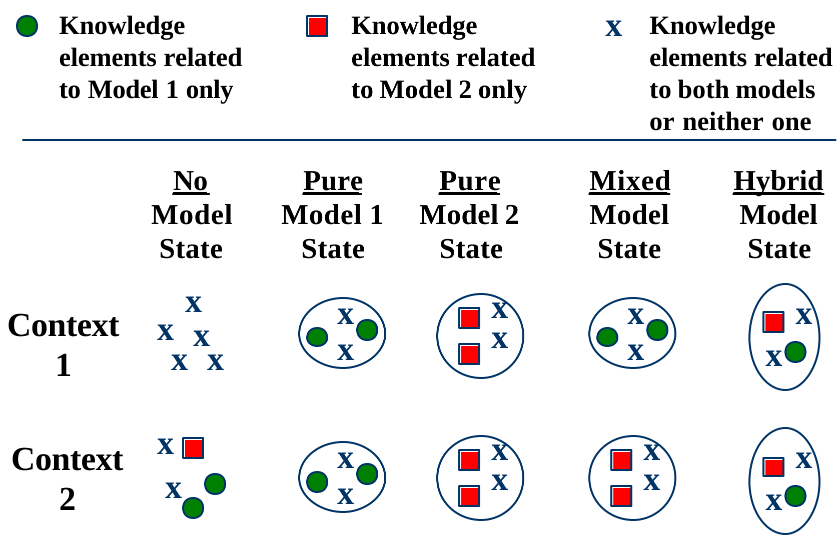

Fig. 2: Mental model states.

Metaphors for mental models and mental model states

Two metaphors seem to be useful for describing and understanding our view of mental models and mental model states. In the first metaphor, we consider a student's mental model analogous to a house in which a student lives. Several features determine the value and usefulness of a house for a student living in it. These features are the:

1. material of which the house is built,
2. arrangement of the rooms in a house,
3. size of the house.,
4. structural integrity, and
5. number of house floors.

In a similar way, there are features that determine the value and usefulness of a mental model for a student who uses it. In this metaphor, there is a corresponding feature of a mental model, for each of the mentioned properties of a house as shown in Table 1.

A house	A mental model
Material of which the house is built	Knowledge structures on a smaller scale than a mental model (mental model features)
Room arrangement	The way in which smaller scale knowledge structures are organized among themselves.
The house size	The extent (number of different contexts) to which a model is applicable
The structural integrity	The student's confidence in his/her mental model.
The number of house floors	The levels of the model. Besides the "basement" level there might be one number of upgraded model variations. These variations can be added and used by the same student in the different contexts or variations can be created and used by different students, each living on its own level --- metaphorically speaking - on its own house floor, as housemates.

Table 1. Analogy pairs between a house and a mental model

The second aspect of this metaphor is related to model states. As houses in our analogy correspond with students' mental models, a model state corresponds to living in a house. Students who have always lived in a single house would be equivalent with those that use a single model in all contexts. Consequently, they are in a pure model state.

Students who live sometimes in one house (apply one model in certain context) and sometimes in another house (apply another model in another context) would be in a mixed model state.

The hybrid model state is a special case of a pure model state (student in a hybrid model state applies a single model in all contexts) or analogously – a student lives all the time in the same house. However, a hybrid house is made of materials that we don't normally find together. For example, if "initial" houses are normally built of wood and clay and "scientifically accepted" houses are built of concrete and steel, a hybrid house might be made of clay and concrete. And although clay and concrete are commonly used as building materials when houses of different kinds are built, together they make a distinctive combination. In the same way, a hybrid mental model is "made of" uniquely combined elements of common initial alternative mental models and scientifically accepted mental models pertaining to a specific content area. Purely from an analysis perspective, a dominant initial (naive) mental model and the community (scientifically) accepted mental model that are related to the same scientific topic represent two "fundamental" kinds of mental models. Elements of these contradictory models are used by students to create hybrid models. In the case of sound those fundamental mental models are the Entity and the Wave "house."

Another analogy that we can use to explain mental models and mental model states (Van Domelen, 2003) is the biological relationship between the horse, donkey and mule, the latter of which is a combination of first two. If a donkey is "initial" and a horse is the "community accepted" transportation means, then the mule is a hybrid one. Accordingly, riding the mule alone (using the hybrid model only) would correspond to a hybrid (model) state. In a mixed (model) state, according to this metaphor, would be a student who rides different animals (uses different models) in different situations or for different purposes (in different contexts).

Contribution to understanding of conceptual change

Among the various theories of conceptual change proposed by previous researchers, our results seem to be in best accordance with Vosniadou's (1994) theory of model upgrading through life experience and formal instruction. She has found an identical type of model fusing in her study of children's understanding of the shape of the Earth, as we did in the case of sound. In our study not only do models hybridize but their aspects do as well. For example, after the instruction, five students from our sample stated that particles of/in the medium will vibrate back and forth and *at the same time* travel toward the listener. This statement was not found before the instruction. From the description of hybrid models stated by single students we have seen that they may be extremely complex and very uniquely composed. Therefore, we believe that another upshot of the concept of hybrid models is that that we will never be able to close the list of mental models related to a particular topic although the majority of students actually share only several models.

The potential biases of the study and corresponding resolutions

1. The sample was not randomly selected. For this reason no conclusions can be made about statistical differences and the possible significance between the interviewed group of students and the class as a whole. However, finding the statistical difference

and significance is never the aim in phenomenography. What we care about is a qualitative description of the phenomenon under study. For our purpose it was significant that official quiz results related to the topic of vibrations and waves showed that our sample was not worse than the class average. They performed just slightly better than 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 had a group of students interviewed only after the instruction. However, results of these interviews allowed for a logical speculation about the extent of the influence of the first interview on the second one. Generally those results confirmed our assumption that this impact is not significant for our purpose.
3. The ratio of female to male students in the sample (2.3:1) was different than in the class population (1.2:1). According to Creswell (1998) a sufficient number of subjects for this type of research is 10 participants. Ideally these subjects would be five male and five female students, so this study involved more than an "optimal" number of students (5) within each of these groups (we had 16 females and 7 males).
4. Determining the model that a student used brings a bias to the classification. This was addressed so that standard reliability checks were conducted throughout the research.

Conclusions

In this study we have identified eight different mental models of sound propagation. Although this number is relatively large, a simple pattern appears in their relationship. We have identified the entity model, which is a dominant alternative model and also most often the "starting point model" in spontaneous reasoning about sound propagation. Another essential model is the wave model, which is the community consensus model. All other models seem to be composites of these two main models as they combine some of the features of the entity and wave model. This class of composite models we have called hybrid models.

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References

Bao, L. (1999). *Dynamics of student modeling: A theory, algorithms, and application to quantum mechanics.* Unpublished Ph.D. Dissertation, University of Maryland, College Park, MD.

Bao, L., Zollman, D., Hogg, K., & Redish, E. F. (2000). Model analysis of fine structures of student models: An example with Newton's third law. *Journal of Physics Education Research, submitted*.

Barman, C. R., Barman, N. S., & Miller, J. A. (1996). Two teaching methods and students' understanding of sound. *School Science and Mathematics, 2,* 63-67.

Brandt, D. S. (2002, February 25). *Constructivist approaches to teaching internet-related topics*. Purdue University, Purdue University Libraries. Retrieved March

02, 2002, from the World Wide Web: http://thorplus.lib.purdue.edu/~techman/constr.html

Creswell, J. W. (1998). *Qualitative inquiry and Research Design: Choosing among five traditions*. Thousand Oaks, CA: SAGE Publications, Inc.

diSessa, A. A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2-3), 105-225.

diSessa, A. A. (1996). What do "just plain folk" know about physics? In D. R. Olson & N. Torrance (Eds.), *Handbook of Education and Human Development: New Models of Learning, Teaching, and Schooling*. Oxford: Blackwell Publishers, Ltd.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29-60). Dordrecht, Netherlands: Kluwer Academic Publishers.

Greca, I. M., & Moreira, M. A. (2002). Mental, physical, and mathematical models in the teaching and learning of physics. *Science Education, 86*(1), 106-121.

Halliday, D., Resnick, R., & Walker, J. (1997). *Fundamentals of physics* (5th ed.). New York: John Wiley and sons, Inc.

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics, 64*(10), 1316-1325.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics*, *Physics Education Research Supplement*,*, 68*(S1), S52-S59.

Hecker, U. v., Dutke, S., & Sedek, G. (Eds.). (2000). *Generative Mental Processes and Cognitive Resources: Integrative Research on Adaptation and Control*. Dordrecht: Kluwer Academic Publishers.

Hewitt, P. G. (1998). *Conceptual Physics* (8th ed.). Reading, MA: Addison-Wesley.

Hrepic, Z. (1998). *Ucenicke koncepcije u razumijevanju zvuka (Students' conceptions in understanding of sound).* Unpublished Bachelor's thesis, University of Split, Split, Croatia.

Hrepic, Z., Zollman, D., & Rebello, S. (2002). *Identifying students' models of sound propagation.* Paper presented at the 2002 Physics Education Research Conference, Boise ID.

Johnson-Laird, P., & Byrne, R. (2002, Dec 18, 2000). *Mental Models Website: A gentle introduction*. Department of Psychology, University of Dublin, Trinity College, Dublin, Ireland. Retrieved Jun, 10. 2002, http://www.tcd.ie/Psychology/Ruth_Byrne/mental_models/theory.html, from the World Wide Web: http://www.tcd.ie/Psychology/Ruth_Byrne/mental_models/theory.html

Linder, C. J. (1987). Tertiary physics: a case study in students' conceptions of sound. In J. Novak (Ed.), *Proceedings of the Second International Seminar: "Misconceptions and Educational Strategies in Science and Mathematics"* (Vol. 3, pp. 322-334). Cornell University, Ithaca, NY, USA.

Linder, C. J. (1992). Understanding sound: so what is the problem? *Physics Education, 27*(5), 258-264.

Linder, C. J. (1993). University physics students' conceptualizations of factors affecting the speed of sound propagation. *International Journal of Science Education, 15*(6), 655-662.

Linder, C. J., & Erickson, G. L. (1989). A study of tertiary physics students' conceptualizations of sound. *International Journal of Science Education, 11*(special issue), 491-501.

Marton, F. (1981). Phenomenography: Describing conceptions of the world around us. *Instructional Science, 10*, 177-200.

Marton, F. (1986). Phenomenography: A research approach to investigating different understandings of reality. *Journal of Thought, 21*(3), 28-49.

Maurines, L. (1992). Spontaneous reasoning on the propagation of visible mechanical signals. *International Journal of Science Education, 14*(3), 279-293.

Maurines, L. (1993). Spontaneous reasoning on the propagation of sound. In J. Novak (Ed.), *Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics*. Ithaca, New York: Cornell University (distributed electronically).

Mayer, R. E. (2002). Understanding conceptual change. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 101-111). Dordrecht, Netherlands: Kluwer Academic Publishers.

Merino, M. J. (1998a). Complexity of pitch and timbre concepts. *Physics Education, 33*(2), 105-109.

Merino, M. J. (1998b). Some difficulties in teaching the properties of sounds. *Physics Education, 33*(2), 101-104.

Redish, E. F. (1994). The implications of cognitive studies for teaching physics. *American Journal of Physics, 62*(6), 796-803.

Reiner, M., Chi, M., & Resnick, L. (1988). *Naive materialistic belief: An underlying epistemological commitment.* Paper presented at the Cognitive Science Society Conference, Montreal.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction, 18*(1), 1-34.

Schecker, H., & Gerdes, J. (1999). Messung von Konzeptualisierungsfähigkeit in der Mechanik. Zur Aussagekraft des Force Concept Inventory. *Zeitschrift für Didaktik der Naturwissenschaften, 5*(1), 75-89.

Taber, K. S. (2000). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science education, 22*(4), 399-417.

Van der Veer, G. (2000, October 15, 2001). *Mental models of incidental human-machine interaction* [www]. Faculty of Sciences, Vrije Universiteit, Amsterdam, The Netherlands. Retrieved Jun, 10, 2002, from the World Wide Web: http://www.cs.vu.nl/~gerrit/mmi9910-report1.doc

Van Domelen, D. (2003). Personal communication.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning & Instruction, 4*, 45-69.

Wittmann, M. C. (1998). *Making sense of how students come to an understanding of physics: An example from mechanical waves.* Unpublished Ph.D. Dissertation, University of Maryland, College Park, MD.

Wittmann, M. C. (2001). The object coordination class applied to wavepulses: Analysing student reasoning in wave physics. *International Journal of Science Education, 24*(1), 97-118.

Wittmann, M. C., Steinberg, R. N., & Redish, E. F. (1999). Making sense of how students make sense of mechanical waves. *The Physics Teacher, 37*(1), 15-21.

Wittmann, M. C., Steinberg, R. N., & Redish, E. F. (2002). Understanding and Addressing Student Reasoning about Sound. Manuscript submitted for publication.