Understanding density and pressure: How students' meaning-making impacts their transfer of causal models

By Regina Ritscher, Rebecca Lincoln, and Tina Grotzer
Harvard University

Presented at the National Association of Research
in Science Teaching (NARST) Conference
Philadelphia, PA, March 23- 26, 2003

The Understandings of Consequence Project
Project Zero, Harvard Graduate School of Education
124 Mt. Auburn Street, 5th Floor
Cambridge, MA 02138

This paper is based on data collected as part of the Understandings of Consequence Project. If you have feedback for us or would like to keep in touch with developments on the project, please check our website at http://pzweb.harvard.edu/Research/UCProject.htm or send us an email at Tina_Grotzer@PZ.Harvard.Edu.

This paper is based upon the work of Understandings of Consequence Project, which is supported by the National Science Foundation, Grant No. ROLE-0106988 to Tina Grotzer and David Perkins, Co-Principal Investigators. Any opinions, findings, conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Acknowledgements

Thanks to Pat Carini, co-founder of the Prospect Center, who developed the methodology used in this study, and acted as an informal consultant.

Thanks to the members of the Teacher/Researcher Prospect Center Summer Institute on Descriptive Inquiry, July 31 2002: Bruce Turnquist, Betsy Wice, Abbe Futterman, Barbara Frailey, and Diane Mullins.

Thanks to all at the Understandings of Consequence Project who made this study possible: David Perkins, Becky DeVito, Sun Kim, Dorothy MacGillivray, Sarah Mittlefehldt, and Rebekah Gould.

A special thank you to the teachers and students who have participated in our research.

In the science classes we are working with, the curriculum is designed to pay careful attention to the scientific details and causal challenges of the topics. Pressure is defined as force per unit area and density is defined as mass per unit volume. Diagrams indicate a pressure differential between forces, a concept that can be applied to many real world situations, from how straws work to how atmospheric phenomena affect weather patterns. Density is described in terms of atomic mass and molecular bonding. Both density and pressure are non-obvious entities, but are demonstrated through experiments to make them obvious. Both topics contain causal structures that allow students to transfer their understanding from one topic to another. These curriculum components are designed to help students frame the topics as scientists do and to a promising extent, they do (e.g. Basca & Grotzer, 2001; Grotzer & Basca, 2003; Grotzer & Sudbury, 2000). However, when examining children's explanations of pressure and density, we found that while learning the underlying (isomorphic) causal forms is an important aspect of the curriculum resulting in significant improvements in students' performance, aspects of students' understanding still includes diverse and particular notions about both topics that include ideas outside the science concepts involved.

> *Pressure inside and outside (the balloon) is like a giant war. If they're equal in size and strength they are able to keep each other in a neutral position but if one gets more powerful, it pushed the other back or forward.* Isaac
>
> *The pressure wants to be equal so the balloon has to replace the pressure.* Kim
>
> *The object that sinks, the water or the liquid can't take its density so it just gives up on it.* Nora
>
> *The atoms (in a gas) just start flying around randomly and when they crash into each other they just change their course and keep moving.* Christian
>
> *When you suck harder, you're putting more pressure on the liquid to rise. You are pulling (a force) the liquid.* Nina

As we read explanations such as these, we asked what we could gain by looking closely at students' scientific reasoning, without beginning with a particular hypothesis or theoretical frame. We adopted this perspective to complement and potentially even challenge, the assumptions and subsequent findings of our larger research study on the effects of introducing students to the causal forms implicit in the science concepts that they are studying (as outlined below). We began to analyze our data in regards to the following questions:

- How do students construct explanations of complex situations involving relationships based on non-obvious properties such as density or pressure?
- Do patterns exist in the ways they construct these explanations and, if so, what are they?
- How do any patterns support or inhibit transfer of understanding from one topic to another?

Background

As children engage in the process of learning scientifically accepted explanations for a vast array of phenomena in our world, they are often asked to adopt ideas and structures that contradict what their experience tells them. This appears to be so in terms of the general patterns of scientific reasoning (e.g. Chi, 1992; Driver, Guesne, & Tiberghien, 1985; Kuhn, Amsel, & O'Loughlin, 1988; Perkins & Grotzer, 2000) and the specifics for individual topics (e.g. diSessa, 1993; etc.) Previous research from the Understandings of Consequence (UC) Project revealed that students' and scientists' explanations tend to have very different types of causal structures at the core, and demonstrated that impacting students' assumptions about the nature of causality is a promising approach for helping students restructure their knowledge and achieve scientific understandings (e.g. Perkins & Grotzer, 2000; Grotzer 2002). However, it is unclear whether students "own" these revised causal understandings to the extent that they are able to transfer them to new topics. Questions relative to transfer are the focus of our current research.

This paper is part of a set of three papers that attempt to offer insight into that question. The other papers in this set report on quantitative and qualitative data that focuses on the question of whether students transfer their understanding to isomorphic and non-isomorphic concepts as well as to learning more generally, and on the question of what role metacognition plays in the process. This paper takes an in-depth look at children's understanding of density and pressure, two topics with isomorphic causal structures. It offers a fine-grained, qualitative analysis of the similarities and differences between students' conceptualizations of density and pressure, with the ultimate goal of showing how these conceptualizations may have aided or inhibited students' ability to transfer their causal understanding between the topics. The paper explores the patterns of learning that students engaged in when building scientifically accepted explanations. It introduces a set of patterns that we found, discusses students' meanings, and considers the implications of the findings.

This paper is based on qualitative data collected in the context of the larger study and analyzed with respect to these questions. However, this paper adopts a methodology that is quite distinct from the others in the set. The primary research questions for the larger study were framed by a wealth of previous research and the findings that emerged from the data in the earlier phase of the project. Here, rather than starting out with a set of hypotheses to be tested or building on the theoretical framework developed from the earlier analyses, we approached student understanding from the ground, up to take a new and different look at students' reasoning—framing the findings by what emerged in this new set of data and from a very open analysis as explained below. The goal in doing so was to offer a different lens on students' understanding and possible influences upon it that might not be captured by the empirical structure of the primary investigations. The methodology and the rationale for it are elaborated below.

This study relates to the broader field of research into children's science thinking in two ways. As part of a larger study it connects to previous findings in terms of what students understand about the nature of causality in pressure and density. Secondly, it draws on a body of literature related to the rationale for the methodological choices made here and how they support the intent of the analysis. The methodology has a long history and it is outlined below.

Previous Findings on Students' Understanding of Pressure and Density

Pressure and density, the topics addressed in this study, present specific problems to students, and there are similarities between the topics that make both hard to grasp. As outlined by Grotzer and Basca (1999), the non-obvious natures of density and of pressure make both topics difficult for students to understand, and the tendency to replace complicated concepts with simpler ones is common. Students often mistake density for weight and force for pressure (Smith, Carey, & Wiser, 1985; Smith, Maclin, Grosslight, & Davis, 1997; Smith, Snir, & Grosslight, 1992; deBerg, 1995), and there is a tendency to substitute active causal agents for passive ones (Grotzer & Basca, 1999). When students picture density, they rarely use the scientifically accepted "particle model" (Driver, Squires, Rushworth, & Wood-Robinson, 1994b), preferring to see it simply as an attribute of a given object. They often view pressure as forceful and one-dimensional, as opposed to a state that is ambient and multidirectional. Lack of awareness of density and pressure as causal agents in their everyday experiences increases students' tendencies to substitute concrete or active causal agents such as weight or force. Ultimately, these inadequate models and conceptualizations prevent students from engaging deeply in more advanced science topics including weather patterns, plate tectonics, and ocean, air and convection currents, as these are all based on concepts of density and pressure.

The approaches that students bring to learning science affect their conceptualizations as well. For instance, according to Chittenden, Courtney and Matz (1981; see also Halford, 1993), students' reasoning begins with their own experiences and observations, and relies on "self-as-model" thinking (as described by Chittenden 1981) to create a conceptual organization for understanding complex phenomena. Self-as-model thinking uses aspects of self-knowledge such as intentions, goals, and hopes as a way to stand in relationship with, and thus understand, the world beyond the self. Others have argued that children evolve sophisticated biology concepts from understanding their own human intentions (e.g. Carey, 1995).

It appears that such approaches to learning impact students' understanding and ability to transfer knowledge between topics. For instance, for the example of "self-as-model" learning, some research suggests that students appear to rely on "self-as-model" experiences, along with their understanding of terms, concepts, laws and principles, and preferred structures to create mental models (Halford, 1993; Kariotoglou & Psillos, 1993; Harrison & Tregust, 1996; Christidou, Koulaidis & Christidis, 1997). Therefore, understanding the approaches that children take to creating meaning can provide insight into what inhibits and facilitates transfer of understanding of scientifically accepted explanations.

The Nature of the Methodology

The methodological approach taken here has a rich history (Himley ed., 2002, et. al.). While the exact steps of the methodology are explained in detail in the methods section below, here we elaborate on the big ideas of the methodology and the rationale for using it in this context.

The approach taken here is a descriptive methodology developed at the Prospect Center's Institute on Descriptive Process.[1] The process begins with open-ended descriptions of student responses for the purpose of determining recurrent headings. The headings provided an organizational frame for charting additional data that, in turn, served to verify the headings by revealing their applicability, overlap and limitations. The process allows making the researcher to make generalizations while maintaining the meaning of children's particular understandings; relatedness between generalization and particularity informs our findings. The process is similar to microgenetics (Siegler & Crowley, 1991) in that it emphasizes an intense analysis of data that provides dense and varied indicators of student understanding over sample size. It is distinct in that data can be charted under multiple headings in order to examine how those headings intersect in a child's explanations.

Headings, as a means of analysis in descriptive research, are distinct from categories in several ways (Carini 1979, 1982). They emerge from data rather than theory, and are refined through charting additional data to reveal factors involved, language used, and subheadings. The same data may be charted under multiple headings, making visible points of intersection between the headings, and recurrent patterns across questions and topics and between students. As a result, the process maintains the cohesiveness of a child's thought, and determines data that is significant in understanding the way his or her knowledge is structured. Finally, the range of data subsumed, involving factual and experiential information, and the application of laws, formulas and models, indicates the influence a particular heading has in shaping understanding.

The methodology was chosen for this part of the larger investigation because it offers an opportunity to consider the outcomes of research through new and varied lenses. It broadens the perspective on the data by engaging researchers to read data who are experienced with Prospect's descriptive methodologies, but not connected to the research at hand. Therefore, they are not limited by previous frames for analyzing the data, and have no vested interest in outcomes. It also involves very deep and careful analysis of the details of student thinking. Together these aspects of the process invite the asking of new questions and can shed additional insight on previous findings.

Methods

Research Design

[1] Prospect Archives and Center for Education and Research began as a school for children in 1965 and grew to include a center for teacher education and research, an archive including about 250,000 works by children (art, writing and other), and books and other publications. Several descriptive processes were developed as a means of respectfully studying children's work and meaning making. These include descriptive reviews of children, teaching practices, schools, and work. All are descriptive phenomenological methodologies inspired by the thinking of Merleau-Ponty and Whitehead among others and developed under the guidance of Patricia Carini.

Twelve eighth grade science classes from a suburban school system in the Boston area where the populations range from lower to middle class participated in the broader study of which this analysis is a part. Data used for this particular study comes from two separate years of our intervention in the school, with six classes participating in the first year, and six classes participating in the second year. Of the twelve classes, students received varying degrees of exposure to the causal concepts (as detailed in Grotzer, 2003). In the first year of the study, the six classes being studied were exposed to five different levels of the intervention, in order to test for their ability to transfer causal forms. One class (the 'causal forms with direct teaching ' (CFDT) group was directly taught the causal concepts central to each of three different units. Another class (the 'isomorphic forms transfer' group (IFT) was directly taught the causal concept central to the first unit, but was not taught the central causal concept in the remaining units, which was isomorphic to the causal form in the first unit. A third class (the causal forms (CF) group) was directly taught the causal concept central to the first two units, which were isomorphic, but was not directly taught the central, non-isomorphic causal form in the third unit. A fourth class (the 'non-isomorphic only' (NFO) group) was taught the central causal form in the third unit only. The last intervention group consisted of two classes given a control curriculum (CON) that included no explicit causal instruction. All of the classes including the control groups took part in inquiry-based science units, co-taught by their teacher and the researchers, that involved Socratic discussion, student modeling of concepts, technological support for visualizing concepts, and investigation of discrepant events. The units covered density, pressure, and heat and temperature, and were presented in the same order to each of the classes. In the second year of the study, the six classes were divided into two intervention groups and a partial control group. Each group contained two classes, one each with the two teachers involved in the study. One group was given complete causal instruction in all three units (density, pressure, and heat and temperature), but also received materials-based transfer support (MTS). Another group was given complete causal instruction in all three units and received materials-based transfer support, but also received teacher-guided transfer support (M+TTS). The last group served as a partial control, receiving causal teaching and materials-based and teacher-supported transfer (CT) for the first unit only and then receiving only causal teaching. Students referred to in this paper will be cited along with their group code, as a reference to the instruction they received.

Students in the intervention classes were engaged in exploring and learning about the nature of the causal forms present in the curriculum concepts. The scientifically accepted model with the embedded causal structure was put forth, along with the models that students brought to the unit, and each was considered for its explanatory power in explaining the evidence in the various activities. The causal units included both activities designed to REveal the underlying CAusal Structure, or RECAST activities (Grotzer, 2002), and discussion about the nature of causality.

Students took a pre-instruction inventory prior to each unit and a post-instruction inventory following each unit. The same three students from each class (n = 36) (balanced groups chosen by the teachers to represent high, medium, and low achievers) were interviewed following each unit. These interviews comprised the primary data for the analysis described in this paper. Relevant work samples were collected throughout the units and classroom discussion was videotaped for later analysis.

Intervention

In each case, control classes participated in a unit that was parallel in all ways to the unit that the intervention classes participated in with the exception of the additional RECAST activities and causal discussion. The units were designed to be the same length so when the causal classes had RECAST activities and causal discussion, the control classes participated in similar activities (without the causal focus) that are typically a part of each unit. For instance, in the causal classes, students participated in an activity where soda cans were made to sink or float by adjusting the density of the liquid that they were floating in. Students in the control classes did an activity where they created an object that would sink, float, or suspend in water by analyzing its density relative to water and figuring out what to add to it.

All of the classes began the year with a unit on the nature of matter after the teachers and researchers agreed that it was a prerequisite for both control and intervention classes to understand the rest of the curriculum. A unit on density and the role of density in sinking and floating followed. A unit on air pressure followed, then a unit on heat and temperature and finally, a unit on geology.

Density

Control classes participated in Basic Density and Intervention classes participated in Causal Density. Each unit consisted of 17 lessons. As an example of what a typical unit is like and how the lessons for causal and control students varied, descriptions of the lessons can be found in the appendix. Density involves non-obvious causal agency in that you can't see density, you need to infer its existence based upon the relationship of an object's or substance's volume to its mass which involves relational causality. The role of density in sinking and floating involves a relational causality. Density is dynamic and can be affected by temperature and pressure. The Causal Density Unit included a focus on these understandings. Both the Basic and Causal Density units included work with Archimedes' Laboratory, a computer simulation program by Snir, Smith, Grosslight, Unger, and Raz, (1989) designed to teach density as a dots per box model.

Pressure

Again, some classes participated in Basic Pressure and others in Causal Pressure that included RECAST activities and discussion about the nature of the causality involved. Each unit consisted of 13 lessons. The units introduced concepts of force and pressure and compared the two. It then focused specifically on air pressure and considered Boyle’s and Charles’ Law. The pressure unit included experiments with balloons in bell jars, straws in flasks, barometers, and so forth. Starks’ Molecular Dynamics was used to illustrate Boyle’s and Charles’ Law at the molecular level. Students were asked to make connections to everyday events through a set of questions presented at the beginning of the unit and revisited throughout. The causal patterns in pressure are isomorphic to those in density. They involve relational causal patterns, non-obvious causal agents, and dynamic variables. In addition, students learned that pressure acts omni-directionally as opposed to uni-directionally as many students tend to believe. The causal version of the unit involved activities and discussion focused explicitly on those particular aspects of pressure.

<u>Assessments</u>

The data that was analyzed was based upon written assessments and clinical interviews collected as part of the larger study. The written assessments were group-administered paper and pencil tasks. The interviews were conducted one-on-one with a researcher, and were about 40 minutes in length. Both assessments were designed to reveal whether students hold a deep understanding of the concepts in each unit, and how they perceive the underlying causality. The assessments were modified versions of those designed and tested in the initial study (Basca & Grotzer, 2001; Houghton et al., 2000) which were based upon instruments by Smith, Carey, and Wiser (1985), and others.

Density Assessments

The density inventory consisted of ten questions. Six questions were open-ended and asked students to draw a model and explain the model for each question. Each question targeted a specific type of difficulty that students have in reasoning about density, one that results in misconceptions or alternative conceptions and that should relate to the structure of their causal reasoning. For instance, one question asked students to explain differences in felt weight between two objects of the same volume. Another question asked students to show the possible outcomes when an object is dropped into a liquid to see if it will float. The questions were balanced so that students had opportunities to reveal that they understood the relationship between mass and volume, the microscopic material causes of density, that as temperature and pressure change density is dynamic, that the relational causality involved in both the mass/volume relationship, and the role of density differentials in sinking and floating. While within topic transfer was not the focus of the study, the inventory was designed to include three open-ended questions in which the students had direct teaching, and three open-ended questions that were near transfer within the topic (for instance, sinking and floating in air as opposed to water). Four questions were multiple-choice in format and each answer was designed to match specific beliefs that students tend to have about density.

> Example: “What happens to the density of an object when you cut it in half?” “Each half of the object is: A) Half as dense as before you cut it. B) Twice as dense as before you cut it. C) The same density as before you cut it.”

The assessment was developed five years ago, tested with approximately 186 students, and refined over the subsequent four years. Some of the questions were from an earlier inventory developed by Smith and colleagues (Smith et al., 1994).

The density interview had five sections, each focused on a certain phenomenon. Some of the sections followed up and elaborated on some of the questions in the inventory. The interview was conducted as a structured clinical interview where students were asked a series of questions and then asked a standard set of follow-up probes. For example, students were asked “Can you tell me more? I want to understand your whole idea.” “Can you explain in more detail?” “Why does it work that way?” “Can you explain what the word [a word the student used] means?" "Why is that important?" Students were invited to draw a diagram or model of their ideas as well.

Pressure Assessments

The pressure inventory consisted of a total of ten questions. Seven of the questions were open-ended and asked students to either draw or analyze a model, as in the density assessment. Again, each question targeted a specific type of difficulty that students have in reasoning about pressure that results in misconceptions or alternative conceptions, and that might relate to the structure of their causal reasoning. For instance, one question asked students what causes the liquid to go into their mouth when they drink from a straw. Another question asked students to explain what causes the wind. The questions were designed to reveal students' understanding of the non-obviousness of pressure as an operative variable in many situations, the omni-directional nature of pressure, and the relational causality involved in many air pressure-related phenomena and concepts, such as pressure differentials, Charles' Law, Boyle's Law, and the application of Bernoulli's principle to lift. Three of the questions were multiple-choice in format with each answer choice designed to fit with certain conceptions that students typically hold. For instance, one question asked how pressure behaved in a fish tank with a fish in it and offered students choices where pressure acted uni-directionally and down, omni-directionally, outside the fish only, inside the fish only and both inside and outside the fish. The assessment was developed three years ago, tested with approximately 162 students, and refined over the next two years.

The pressure interview had seven sections, six sections focused on a certain phenomenon and the final section focused specifically on the transfer of causality. Some of the sections followed up and elaborated on some of the questions in the inventory. As with the density interview, the pressure interview was a structured clinical interview with a standard series of questions and follow-up probes. Again, students were invited to draw a diagram or model of their ideas as well. The final section offered scaffolded cueing of the causality involved where students were asked increasingly targeted questions about the nature of the causality involved until if they didn't spontaneously mention it, they were asked a direct question such as: "Does what we learned about relational causality help you to think about any of the questions here?"

Analysis Technique

Initial Reading

A fine-grained analysis of the group-administered inventories and individual interviews was conducted. Initial reading, listening and partial transcriptions indicated that the students understood pressure and density in ways that made use of, but were not entirely congruent with, scientific concepts and information. In order to gain insight into the complexity of their thought, we investigated the question "What meaning do children make of density and pressure, and in what ways do they bring this meaning to applications of related concepts?"

Determining Headings

The analysis began with an open-ended description of student responses for the purpose of determining recurrent headings. These headings provided an organizational frame for charting additional data that in turn served to verify the headings by revealing their applicability, overlap, and limitations. In order to determine initial headings, we brought the written responses of five students, chosen for their complexity and diversity, to a small group of teacher/ researchers at the Prospect Center's Institute on Descriptive Process[1]. These teachers, all experienced with Prospect's descriptive methodologies but not connected to our research, and having no vested interest in the outcomes, analyzed the children's responses through a process called "close reading." The protocol begins with the group paraphrasing a response in order to focus attention on word choice, syntax and organization. Next, the response is described in detail, one section at a time. Our analysis of this data included descriptions such as "based on the picture, the warm air seems to have more dots per unit area" and "the answer refers back to the question and incorporates the word density." Finally, the response was re-analyzed, sentence by sentence, allowing for a more interpretive approach : "he never uses the word 'cools' yet cooling should be firmly within his life-long experience." The initial headings emerged from this analysis of student responses and were then used to chart a larger selection of our data.

Testing the Headings

One researcher extensively charted the data from the first year of this phase of the study. She listened to all interviews to date (n=18) and read a subset (n=60) of the pre- and post- inventories. This researcher, the first author on the paper, was new to the broader research study and least familiar with the ideas framing it. The results were then reviewed for relative frequency of occurrence, type of information, language and arguments included under each heading, and prevalence in both density and pressure work and in particular questions. The specific examples that comprised the data were analyzed through close reading in order to more fully understand what we meant by each heading, and what questions and subheadings were included. Finally, the data was considered in light of three questions: What does this heading reveal about the ways children structure their knowing of science in general and of causal reasoning in particular? What strengths and confusions does it seem to foster? What changes are indicated for the curriculum being offered? As a further test of the headings, certain responses, chosen for their complexity were "close read," using the descriptive methodology described above, by a group of researchers who were unaware of the headings. Two researchers then analyzed transcripts of eighteen interviews collected from the density unit in the second year of this phase of the study, looking for ways this data concurred with and differed from our initial observations.

Reliability was gained through use of the same protocol in our own work and by independent researchers expert in the methodology. In addition, two researchers, charting eighteen interviews independently, examined the data for the recurrence and relevance of these headings, looked for data falling outside the initial headings, and collaborated in the formulation of findings. As a phenomenological study, our research was designed in terms of trustability (Carini 1979, 1982). Trustability relies on a study's internal coherence and its public nature, which means that the same process can be carried out by others and that data and analysis are shared as part of the findings, and its durability. Coherence in our analysis is demonstrated by the concurrence of the headings based on description done by two separate groups of researchers and their recurrence across students. Coding data in terms of multiple non-exclusive headings recognized the recurrence and divergence of information, concepts and language used to express thinking in science. The use of close reading in discerning the internal coherence of a student's explanations maintains their wholeness and particularity, and respects the students' choices. The use of consistent and systematic procedures for reading student work, charting data and refining headings meant that analysis could be repeated by separate individuals and groups of researchers in a way that enriched our findings. Durability was established through including data for six or more questions in each of two units, the use of pre and post-tests in addition to interviews, and inclusion of both density and pressure data in explicating the headings.

The analysis of the data was carried out blind to whether the information was from a pre- or post- test, and in what intervention condition the student participated. The interviews were all post unit interviews so it was not possible for project researchers to analyze these blind to this information. This information was only considered afterward as a means for fleshing out the broader context of each student's experience, and to add to the possible interpretations for why students responded as they did.

Findings

It is important to recognize that our study resulted in "findings" rather than conclusions, which indicate the range and variability of these students' thinking (Carini, 1979). Our findings provide a rich basis for furthering our understanding and research, contribute to the body of knowledge of children's thinking in science and invite verification and extension through the work of others. While we charted the findings in terms of common headings, each child's response provides an extensive sample of her or his understanding in its particularity. Therefore the generalizations made express the variability as well as the coherence within each heading. Our findings provide information on what ideas students use to make sense of the world, how they use them to structure their knowledge, and the ways they support or hinder the development of scientific ways of thinking, particularly as it relates to causality. It is important to realize that these understandings are partial (Carini, 1979, 1982) but significant and resulted in greater attunement to what children's explanations mean for them and a heightened capacity to strengthen the curriculum we offer them.

Analysis and Findings

The initial close reading (carried out at Prospect Center) provided six tentative headings that shed light on ways our students seemed to structure their explanations:

- Static versus Dynamic Models
- Preference for Concrete and Bounded Entities versus Continuous Entities
- Self-as-Model Reasons
- Multiple Definitions
- Partial Understanding
- Decontextualized Models

As we charted our data, we found that the same data was appearing under "Preference for concrete and bounded entities versus continuous entities" and "Decontextualized models" and so the latter heading was dropped and the headings were collapsed. The close reading done on the second year data by project researchers did not reveal additional headings. The analysis presented here describes the data charted under each of the first five headings along with the impact this seemed to have on children's ability to grasp causal relationships and to transfer their understanding from one topic to another.

Static versus Dynamic Models

Students used both static and dynamic models to describe density and pressure. Static models are ones that describe or draw a fixed structure or offer a frozen snapshot of a process. Examples in density include "dots-per-box" models or models showing molecular structure minus kinetic energy. Dynamic models explain what is going on in terms of movement; pressure as a push is an example. What sort of confusions might result from holding each type of model? How might each shape causal understanding? And how does using a particular model about one topic might help or hinder understanding transfer of understanding?

The following examples both compare the density of brass and aluminum cylinders by describing them in terms of molecular bonds. Alex relies on a static model, while Christian develops a more dynamic one.

> *Right now I'm drawing the three causes of density. Right now I'm drawing the atomic mass of the compound, the object….This already has a larger mass than the aluminum because of the way the protons and neutrons line up and how many protons and neutrons it has …..right now I'm drawing the atomic bonds and how they might relate to density. If the atomic bonds are stronger then more of them can fit into a space, if the atomic bonds are weaker, less of them can fit into a space….. Now I'm drawing structure which is also part of the second cause of density. I'm trying to draw a crystal-like structure which may have to do with copper. Crystal-like structures seem to be stronger than regular or square-like structures for some reason.* - Alex (CF)

> *At the molecular level there (are) atoms and bonds and depending on the bond size is how close they pull together. If they are really far apart they will be stretched out and not as dense. And the atoms are made up of electrons, protons and neutrons. A greater amount of them makes the atom more dense or less dense...... When they take the mass of the atom, they can only measure the neutrons and protons because the electrons are too small and too fast, they can't get an accurate measure on them.*
> - Christian (M+TTS)

Alex discusses atoms and molecules in terms of numbers of particles in a space, positions, bonds and structure not as energy or movement. His language is exact and structured, which gives his explanation a sense of measured precision. He pictures atoms as lined up. Christian describes the space it takes up in terms of the actions of pulling and stretching and explains the energy and movement of particles. He accepts the difficulty of locating electrons.

Similar differences occur in student's thinking about pressure and what causes a balloon to deflate when it changes altitude.

> *The pressure was lower on top of the mountain because there was less layers of atmosphere pressing there, so, and air pressure is the weight of all the air particles and so when she came (down the mountain) there was a lot more air pressure on it. And so, because the pressure that the air inside the balloon was exerting was not as much as the air pressing on it, so it got partly deflated.* - Anna (IFT)

> *Say there's ten Newtons of pressure pushing outside from the sea level air and it has only five Newtons on the inside from the higher elevation. Now technically, the ten is going to be stronger than the five, so when they push, the ten is obviously going to overpower the five and compress it.*
> - Christian (M+TTS)

Although there is movement in the balloon's deflation, Anna's explanation focuses on the balance expressed in weight. On the other hand, Christian uses the words "pushing," "overpower" and "compress" allow of which evoke an active and dynamic image.

We found that students developed static and dynamic models on both micro (atomic) and macro (object) levels. While atomic structure is often taught through the use of static diagrams, atoms can be accurately described as energy and motion and some students build their explanations in these terms.

> *Maybe the heat causes sort of a magnetic field that an atomic bond gives off, but more like a vibration that goes through the molecules to be more active and move around faster. This causes (the hot air balloon) to expand more.* - Sam (CT)

While we found density was somewhat more likely to lead to static models and pressure to dynamic models, students most often relied on one type of model over the other in most or all of their explanations. Consideration of a situation as static or dynamic is in many ways separate from understanding the causal relationships involved. Static models considered objects and non-obvious elements such as pressure or density in terms of a comparison of qualities: "*The object will float because its density is less than the liquid's* Justin (CT), or "*The pressure inside the balloon is less than the pressure outside"* Karla (NFO). Alex's (CF) description of sinking and floating contains motion but is constructed in terms of before and after diagrams, the constancy of the line, and the sameness of the densities.

> *Its density causes an object to sink or float. If the object has a density greater than the liquid it will sink. If the object has a density less than density of the liquid, it will float. If it has the same density then it will suspend. It won't float, it won't sink…I'm drawing a box filled with a liquid which has a line to it where it is going to be staying before the thing*

is dropped in…Before we drop it in the water line should be relatively the same. After it should rise because of water displacement because you can also get volume from water displacement. The density of the water will stay the same and so will the object but the object won't float because it doesn't have a density lesser than the liquid so it falls.

- Alex (CF)

He is able to see things as changing over time but misses the dynamic quality of density. It isn't until he thinks in terms of movement, as he does in describing the hot air balloon, that he is able to describe things as changing.

The heat source heats up the air to make the atoms move around and become less dense and the density of the helium is less than the air around it so it floats up in the air itself because of its density… Its atomic bonds weaken because of the heat. The heat causes them to move around more and causes it to rise… movement.

Even here the step-by-step outline gives his explanation the feel of a set of static snapshots rather than a moving film.

Dynamic models were explained in terms of action: "*The object is heavier so it goes through the pressure (and sinks")* Melissa (NFO), or "*The pressure is pushing in on the balloon, making it deflate"* Joey (MTS). Sometimes the importance of the action seems to interfere with the ability to explain causality as it does for Jonathan (M+TTS).

One pressure is greater than the other one, or something like that. And this pressure overpowers this one, so this air would continue going that way. And all the air, there'll be many of them, like that, overpowering other air, so all the air's going this way at one time. So, that would cause the air to move as in wind.

Here he confuses the pressure of the air for the force of the wind. Christian (M+TTS) creates a dynamic/ causal model in wind.

It's probably the pressure that is pushing around all the wind which creates the wind speed, by having more wind pushing on it… It may have something to do with pressure changing a little bit which creates the wind.

While this answer does not fully recognize the causal relationship between pressure systems which causes wind, he is able to see that the wind results from differing pressures rather than from the pressure itself. His diagram of how wind forms demonstrates thinking that incorporates a step-by-step element.

I'm drawing wind and changes in pressure. Each line going through represents a change in pressure. The squiggly lines going through the middle is wind.... (the numbers above them) show that you're changing the pressure by one Newton per graph. The way it is picking up and increasing strength, just by changing the pressure.

This stood out as dynamic drawings used long curving or jagged arrows, with a clear sense of directionality and movement but which often had a scribbled feel and generally lacked detail. Static models used short, straight arrows, numbers, and formulas. Jake's (CF) explanation shows that he clearly considers movement with a step by step frame and that he understands the relationship between pressure and wind.

> *When air move, it leaves less air behind it. There is less air pressure. So the air around it, which has more air pressure, moves into it. Higher pressure moves into lower pressure.*

Static Models vs. Dynamic Models: Findings

While we found density was somewhat more likely to lead to static models, and pressure was more likely to lead to dynamic models, students most often relied on one type of model over the other in most or all of their explanations. It seemed to be a matter of preference whether they pictured a situation more clearly as diagrams or still pictures, or in motion, and students used their preferred model across topics. However, while both types of models were used equally effectively in making comparisons and could be used to explain causality, the capacity to combine static and dynamic models was useful in considering moving systems. We found that while Jake, who combined both elements, was able to explain what causes wind, students who relied on a dynamic model tended to equate wind with pressure itself. Students who employed highly static models had the most difficulty with this question, and related it to other elements such as the ocean or the movement of a fan. It is preferable to provide both models as part of a curriculum. Not only do some students find one model more useful in their thinking, but systems contain both structure and movement.

<u>Concrete and Bounded Entities</u>

A preference for thinking in terms of concrete and bounded entities shows up in many students' answers. Here, Rachel (CF) answers a question on why a balloon deflates when it is brought from the mountains to the beach.

> *The elevation decreased when going from the mountains to the beach house. As elevation decreases, the pressure increases. The balloon was being pushed in by the pressure. It could have popped, but some of the air must have seeped through the knot on the balloon.*

Her explanation begins with a clear and unrefutable fact: elevation changes. Having stated this, she goes on to relate it to a change in pressure: elevation decreases, pressure increases. This is a wording many of her classmates also use and has a memorized feel to it. Her reliance on fact as the basis of a simple, logical construction for her answer allows her the confidence that she understands the whole picture. This tendency is reflected strongly in our scientifically oriented culture, which teaches us to prove theories with "hard facts," formulas, laws, and step-by-step methods that isolate and control for variables as a way of reaching an unquestionable truth.

While Rachel's scientific reasoning relates to pressure and could have led into consideration of the air inside the balloon, her last sentence cites her everyday experience with balloons that leak and pop. She considers what the balloon does, rather than how the air inside it changes. Rachel's explanation begins with factual information that she knows to be true and ends with experiential knowledge that feels just as solid. Each part of her explanation has a bounded-ness to it. There is a feel of certainty, although her explanation fails to recognize the pressure inside the balloon or the fluid nature of air.

Preferences for thinking in terms of concrete and bounded entities over fluid continuums show in students' explanations in several ways. Some create very graphic visualizations of what happens by describing a concrete and limited space.

> *The two objects are different in mass because of what is going on inside. Object A has molecules that are very tightly packed. Also the molecules are more massive than object B. Object B has molecules that are much more spread out and have less mass.* - Janet (CF)

> *Wind is caused by the difference in pressure. If there is low pressure inside a tube that is covered and high pressure outside and if you open the cover, the high pressure will rush into the low pressure area.*
> - Kiran (IFT)

Students often construct answers that feel complete and convey a sense of certitude and trustability: "I know this." Some do this by focusing on specific materials: "*the rock is more dense than the water*" (Rob, IFT) or *"water has a density of 1g per cubic centimeter while the balloon's only 0.3g per cubic centimeter"* (Russell, CFDT). Numbers are used as specifics in Russell's explanation and provide a sense of parameter to Detmar (CON) visualization, *"the one (balloon) in the mountains has only 3 to 5 layers of air on it and the one at sea level had 15 to 16 layers of air on it."* Phalen (CFDT) trusts calculations:

> *The first object has a volume of 16ml and a mass of 32g. If the density equals mass divided by volume then the density of the first object's density if 2 g/ml. If the second object has a volume of 20 ml and a mass of 60g, then the density of the second object is 3g/ml. Therefore the second object's density is higher. The second object will feel heavier.*

The language students use in their answers also has a feel of boundedness when determinant and forceful language is used to convey certitude: "always have," "must be," "that's the way it is," "determines." Phalen uses the word "therefore" to emphasize why things happen, a word that was common in student's explanations. Statements like Virginia's (CF) *"Force pushes the air molecules through the air"* contain a positive energy with little sense of doubt or question. Laws are often understood as "always" and the memorized feel to the language used conveys this: *"Density is mass per unit volume"* David (IFT), "*Wind happens because of Bernoulli's principle which states as the speed of a fluid increases, pressure increases"* Gillian (CF). Sometimes, as in Gillian's case, the laws become reversed (actually, as temperature decreases, volume decreases; as speed increases, pressure decreases) and in these cases the certainty of their language becomes problematic.

Language helped students remember information and organize their answers. Answers began by listing the number of possibilities: *"There are three possibilities to the* *results of an object which is dropped in water. The object could float, suspend, or sink."* Nick (CF), and *"Temperature is one of the two things that can cause density to change. The other is pressure."* David (IFT). Language also shows the constraints that shaped students' understandings. Many relied on "normal conditions" that were considered a standard: *"The air mass rises or sinks until the air changed back to their regular form of density"* Clem (CFDT). It shaped comparisons, which were often between two distinct items or situations through use of language such as "is/isn't," or "either/or," *"The water would either be able to hold the object up or the water would hold the object down"* Isaac (CFDT).

Concrete and Bounded Entities: Findings

Despite its possibilities for inaccuracy, the capacity to think in terms of concrete and bounded entities seems to be a positive support for causal thinking. It allows students a visual-ness of description and representation that fosters a clarity of mental model. This provides the means for finding starting points and distinguishing different elements and encourages a sense of confidence and control that allows one to "play with," or change, various elements. It plays a role in helping students develop the capacity to recognize the relevancy of prior knowledge and helps them talk through processes. These elements also help students transfer their understanding from one topic to another by transferring facts, formulas, and the capacity to build step by step processes. Clement (2000) found that scientists often work flexibly between different representations of a problem, playing with the concepts, adjusting how the problem is defined, and shaping their understanding through this process. However, relying on laws, formulas and bounded models can be problematic. Rosemary (CF) understands several aspects of pressure but isn't sure how to use them to develop an explanation of the pressure involved in a hurricane. She understands that *"Pressure is force divided by area,"* that it is *"Pushing with a force,"* and that *"If I want to change the pressure I can go at a greater force."* These understandings confuse her when she tries to explain wind. *"I know that for Bernoulli's principle it said that when a fast rate, a faster velocity, the pressure isn't as great, but it has to be a smaller area, so I don't know how it applies."*

Explaining causal understandings comfortably requires the capacity to simultaneously rely on and step free from bounded entities, to at the same time use clear and concrete facts, laws, and concepts, and yet to question reflectively where each may or may not be appropriate. Causal structures in the world are relational, rather than linear, and complex, rather than simple. Accounting for variability requires a student to envision an ever-changing balance between a multitude of factors. Jake (CF) shows this sort of awareness in his description of sinking and floating.

> *You have to look at the density of the object. You have to look at the density of the liquid. If you take water, for an example, which has a density of one at standard temperatures, then if the density is .5 grams per milliliter (it has to be in the same units) then it would float and if the density was more than one, say 5 g/ml, then it would sink…. And if it was exactly the same as water, exactly one, then it would neither sink nor float completely, but would stay in the middle unless there was a force against it, like a current.*

While Jake's explanation is bounded through the use of a specific substance, water, and through calculations, he is also aware that at a different temperature conditions would change and that there are other elements, outside of the density he is discussing that could affect what happens. He seems comfortable with the idea that his answer might not always hold. In order to support causal understanding, curricula need to combine laws, formulas and facts with consideration of the variability and possibilities that exist in complex systems.

Self-as-Model Reasons

In self-as-model thinking, students predict that an object will act in the same way they themselves would. We found that our students frequently explained things in ways that indicated they were thinking in terms of emotion, agency, and volition, and from a view of the universe where things happen for a purpose rather than as a result. The overlap between self-as-model thinking and reason in place of cause lies in the nature of reason. Humans are active agents and do things for a reason, with a sense of purpose in which they have some choice or volition. Reason is shaped by need and emotion as well as by logic. At times, students' language and explanations refer to agency, need, will, choice and emotion. Examples of the sort of language used are given here. Words and explanations that express active agency, volition and a sense of purpose included:

"makes": *"Helium makes things go up"* Jeff (CF)
"The heat will make the molecules move faster and spread out" Don (IFT)

"tries" : *"The air tries to escape from the hole in the balloon"* Catherine (CF)
"The wind is trying to get stronger" Isaac (CFDT)

"force": *"The air that is being sucked in is forcing the liquid to come with it"* Rob (IFT)
"Something is forcing the wind to move together." Don (IFT)

"purpose": *"The warm air rises so it can sink"* Melissa (NFO)
"The warm air can't leave because it holds the cold air down" Aaron (CF)

Words connected to human feelings, needs, traits and capacity for responsiveness.

"Liquid wants to move at that speed." Sarah (CON)
"Air wants to get rid of the strange substance (helium)." Samantha (CON)
"The hot air rises because it needs to get high in the sky and the cold has to get low." Rob (IFT)
"It just had to get out of the container." Rob (IFT)
"The air is stronger than the liquid so it can pull it up easily." Jane (IFT)
"It is cold in the mountains and the balloon got used to it."

Justin (CT)

"Gold can't handle the heat and pressure."

Kiran (IFT)

"Where the air pressure is less, the particles feel more relaxed and come closer together." Anna (IFT)

Often, reason-based logic forms part of a more scientifically standard causal explanation:

They (air molecules) want to stay in motion because of inertia. Inertia states that an object in motion wants to stay in motion.

Alex (CF)

Once matter starts moving it doesn't want to stop moving and once it stops it doesn't want to move again. Christian (M+TTS)

It's almost gravity because one molecule is almost pulling another one to the first one so there is getting more and more force…It might be gathering some with it because of gravity…They maybe gather other ones to increase the force…Air molecules are always trying to…kind of move apart." Alex (CF)

Both inertia and gravity are important scientific concepts. The introduction of "wants" and "trying" and "gathers to increase force" imply a sense of reason.

Self-as-Model Thinking: Findings

This language/thinking seems to be displayed evenly between pre and post unit inventories. Some students were much more prone to talk in these terms than others were, and some questions seem to invite such language/thinking more than others, in particular, questions about balloons, hurricanes, warm air rising, and the flask. There were many more examples dealing with pressure than density. Part of this may be due to the fact that pressure, thought of in terms of force, feels much more "active" than density, so that language and ideas of active agency, will, and motive seem more natural, as does reaction on the part of the recipients.

Humans have a preference for making sense of things in their own model. Part of this is due to the fact that we first know the world experientially, and that while this may involve a great deal of careful observation and experimentation, it also includes affective qualities - from delight when raisins sink and then rise, to despair when a balloon pops, to fear when a hurricane damages our homes. In addition, as we seek to organize our knowledge, we impose our own sense of structure onto the world.

Scientific knowledge can certainly increase the accuracy of reason-based logic without prohibiting thinking in terms of purpose. The use of story, imagery and animation can allow entry into new concepts. In fact, scientists themselves often use imagery and the language of "wants and "tries" in their own work. Zohar and Ginnossar (1999) have argued that anthropomorphic reasoning does have a place in science classrooms, that it is a short-hand way of talking that students use while recognizing that the entities involved are not really intentional. However, in their work Lakoff and

Johnson (1980) have found that the metaphors we use stem from our way of experiencing and understanding the world, and many of our students' explanations would seem to support this. Care should be taken to notice such language and the sort of thinking it engenders, as well as to discuss why things happen as they do as part of science teaching.

Multiple Definitions

Density and pressure are complex topics that our units have approached in a variety of ways. As a result, students develop different ways of understanding and talking about these subjects. They use verbal definitions that they have learned, which can involve terms that can be understood in a number of ways. Students develop other definitions based on their experiences and on images developed from class examples. This explanation of sinking and floating allows us to examine the different ways Isaac (CFDT) defines density, the terms he relates it to, and the way he constructs his answer, both resulting from his definitions, and favoring his choice of some over others.

> *Sinking is caused by the density of the liquid and the density of the object. If you have an object that is less than the density of the liquid you would have it float but if it's more then it would probably sink, and if it's equal it would suspend. If you put one object in the same liquid it would sink, but if you put another object it would float. It's because of the fact that it's a different density, so it would cause it to sink and float. (When it suspends) I think that the pressure is the equal around the entire object so it's able to stay in the water without hitting the bottom or getting to the surface again. The molecules sort of hold it up from getting sunk. When an object is sunk the gravity of the object keeps it down to the bottom but when an object's in the process of sinking, the water molecules move out of the way because it's so heavy that they can't hold it up so gravity takes control and pulls it down to the bottom…When it's sunk the water moves over into its proper place and keeps the object from coming up again. The water's density allows it to keep its strength and if the density is greater, then the object is stronger than the other one, then it couldn't hold up so it will fall down to the bottom. Density means the space a certain object can take up. Like for example water is the standard which is one and steel is, I don't know…because of the fact that if any object has mass and volume, it always has density. This is a property of matter.*

Isaac defines density as a property of matter; he begins by referring to the "density of" things. He also defines it as space and as mass and volume. These definitions result in the student considering density in particular ways. Since it is a property, it can be used in making comparisons. However, density isn't active. Isaac says that "you would have it (the object) float" and "it would probably sink. He thinks of density differently than he does pressure, gravity, temperature and molecules all of which exist in themselves and play active roles in what happens. The most active density becomes is in "allowing" strength, in itself an odd construct. While density is taught as the relationship of mass to volume, and Isaac uses his knowledge of this, he ties his definition of density to size.

Density could change by the temperature and pressure…The pressure causes the object to gain, to sort of lose some of its volume so it could get more dense than the object and so could the heat depending whether it's cold or hot. When it's warmer, it would cause the metal to expand so the volume would be higher and it would be less dense and if it was colder it would be able to scrunch up again and be more dense. Since the atoms are getting excited from the heat, they start to lose their atomic bonds……It can expand but only if there's heat. It wouldn't happen at room temperature and standard pressure.

Changes in volume are easily visualized as a sort of active linear causality: temperature causes atoms to move, which causes their bonds to expand which causes volume to increase. This type of explanation seems to be comfortable and clear to Isaac and plays an important role in how he structures his explanation.

Students also held multiple definitions of pressure, as the following interview answers of Rosemary's (CF) illustrate.

When you suck into the straw, the pressure in your mouth is greater than the water pressure, so the water pressure can't keep the water in it cause the atmospheric pressure is greater so it pulls up in the straw, like a suction. It comes up in the straw because the air from your mouth when you are breathing up it is greater than the water pressure, so the water can't keep itself in the cup, it has to go up through the straw.

I know that for Bernoulli's principle it said that when a fast rate, the faster velocity is, the pressure isn't as great but it has to be in a small area so I don't know how it applies to that…this is what I think, when the velocity does get greater so that everything is harder. I think like the wind is stronger and stuff like that so, I think, the pressure decreases, it's either increases or decreases, I can't remember. So the pressure inside the house becomes stronger than the pressure outside, either that or the pressure outside becomes stronger than inside…So then it pushes on the windows. If they are closed, it can break the windows.

Pressure is force divided by area so it's the amount of force in newtons on an area in centimeters squared so it would be pressure equals force divided by area. So a pencil tip, this pencil, if I'm pushing at the same force and then if I do it like that (the eraser end) this area is larger than this area, so the smaller area the greater pressure so the tip would obviously have a greater pressure than the eraser. To change pressure you need to change the force.

The higher up you go the less…the pressure decreases but in the water the pressure increases and so whenever the pressure changes, your ears pop. When you go up in a plane, when you travel upward, your ears pop. When you go underwater and you travel downward, your ears pop. It's just a sign of changing pressure.

Rosemary defines pressure as force divided by area and her acknowledgement of units, newtons and centimeters squared, show that she understands it as measurement. She focuses on the force, saying that it is what you have to change if you want to change pressure, but in her examples it is the area that changes. Rosemary doesn't define pressure in terms of weight or movement, and feels that pressure is unrelated to wind. In understanding pressure as force, she thinks of it as both a push and a pull All her answers are stated in terms of a differential and of pressure as changing, thus indicating that she has a sense of relational causality. However, she explains that in a straw one pressure is greater so it pulls the liquid up. The idea of a pull sounds like a tug of war, in part because her answer also expresses a sense of personal agency for the "actions of the water pressure and the water," which can't keep the water in the cup and "has to go up the straw." Her definitions have an affective feel.

Multiple Definitions: Findings

We found that students' definitions of density fell into three categories: as a property of a material, in terms of either space or weight, and as a relationship between mass and volume. Thinking of density as a property was clear (water has a density of one which is less than the density of gold) but did not help students to understand what makes something more or less dense, or to realize that it can change. Defining density as space or weight did not allow students to truly understand the relative causality since it is important to define it as a relationship between mass and volume. Pressure was defined as a force, an agent, weight, movement, a differential, or a measurement. In general, understanding pressure as movements caused incorrect explanations, while equating it with weight helped students see pressure as a differential.

The definition a student used at any point was the one that seemed most clear or certain to a particular student in a given situation. Terms and formulas feel scientific and can be memorized. Experiential definitions feel trustable because they recall what one has personally seen or done. Images rely on visual memory that may be strengthened by affective experience. The type of definition used affects the understanding of the concepts involved. How a student defines the terms being used impacts his or her capacity to transfer understanding from one topic to another. It is important to recognize the definitions students gravitate towards in order to determine what is clear to them. At the same time, students should be taught to recognize the varied definitions they use, what type they are, and where they are helpful and limiting.

<u>Partial Understandings</u>

In complex situations, understanding is nearly always partial, and most of us eventually hit the limits of our understanding when asked to elaborate. This was true of our students as well. Their explanations are based on scientific knowledge, observation, and experience, and contain information that is accurate, clearly expressed, and seems "solid" as well as knowledge that is hazy, changeable, or missing. In addition, in explaining complex situations, children often choose to rely on certain of their knowledge while ignoring other factors or concepts.

Partial Understanding of Density and Pressure

Meg's (CFDT) explanation of a Galileo Thermometer.

> *There's obviously different liquids because they're different colors. And then there's water around…I just know that there's different liquids and it depends on their density and the density of the water and the temperature around…If this one's kind of floating right now it means it has liquid inside that is less dense than the water and when the temperature rises this liquid might change and the density might change and then you would see it at the bottom…Right now because it, because this thing is cold, the liquids inside, the molecules are tightly packed and if heat is applied then they move further apart or they start changing their density or like the bonds change. I don't know if the number of protons and neutrons change but I know that something happens because one floats and you can see it sink if you come back in a couple hours…If you apply heat I think sometimes that the protons and neutrons get heavier. I don't know how to say it but the protons, they get more mass and that's why some of them sink…If you apply heat to some things they change like the protons and neutrons and the bonds or the air pockets inside, they change because of the heat that was added, I don't know, that's what I think…It might (change the number). Because of heat you can have different reactions and the liquids and the protons and neutrons, you might get a totally different liquid. You might start out with one but end up with a totally different liquid because of the number of protons and neutrons.*

Meg understands and uses a lot of scientific knowledge:

- The thermometer works because the balls in it sink as it warms up
- Different liquids have different densities
- Sinking and floating involve relational causality; things sink when they have greater densities than the liquid they are in.
- For something to sink, it must have more mass on the particle level (either weight or number)
- When objects are heated density changes and the molecules move further apart
- A particular material can't change its number of protons and neutrons
- Heat can cause reactions in which materials change

She understands the relational causality involved in sinking and floating, and explains packedness in terms of molecular bonds and atomic weight. Meg also realizes that a particular material always has the same number of protons and neutrons. Examining her other answers show this knowledge to be both solid and flexible.

> *The object, which has a greater density than that of the liquid, sinks because its bonds are tighter and it has more protons and neutrons and I don't think it has air pockets.*

> *You can change the liquid instead of the object. You can add things to liquid to make density greater.*
>
> *Density has a standard temperature and they say that the density never changes in our book but that means at a standard temperature so when you heat something, when we heated the ball and we tried to pass it through the ring, it wouldn't go because the molecules expanded.*

The dilemma, or central but unstated question, she seems to be struggling with is "if being heated causes molecules to move further apart and objects to become less dense, why do these balls sink when the temperature increases"? It would seem that she has the information she needs to figure it out, but here she only thinks in terms of the temperature changing the density of the balls. Thinking about the density of the balls alone requires building a complicated explanation to account for the fact that, while she understands that increased temperature causes lower density, these balls sink and, therefore, obviously have more density. She handles this by theorizing a change in atomic weight and uses the heat as an agent for a chemical change. Two questions came to mind for us as researchers. First, why when the balls behave in an unexpected manner, doesn't she reconsider the entire system? This is a large question as students often find it hard to change direction in this manner. Secondly, what is her understanding of heat? Here, the thermometer changes based on a small number of degrees, while the heat needed to cause a chemical reaction is generally considerably more. However, she uses the term *when heat is applied* which suggests the image of more heat than a change in room temperature.

Meg knows that her understanding of the science she is trying to explain is only partial. Throughout she uses the words "might," "sometimes," "I don't know…but I know..," "I think." She isn't sure; things didn't happen the way she expected them to. She brings a wide understanding of science to create a complex answer, but really isn't sure this is what happens here.

Students' explanations of pressure showed a similar mix of accurate, inaccurate and wrongly applied knowledge. Equating pressure with force, rather than considering its relationship to weight and density showed in many explanations.

> *When you suck into the straw, the pressure in your mouth is greater than the water pressure, so the water pressure can't keep the water in it because the atmospheric pressure is greater so it pulls up in the straw, like a suction.* - Rosemary (CF)

> *The wind works by blowing and it puts pressure on things such as the tree, which causes it to move. The wind has more pressure than the tree so it moves. The wind, however, doesn't have enough pressure to move a building.* - Janet (CFK)

Partial Understanding of Air

Many of the students in the study, as in the general population, had trouble understanding the nature of air and the role it plays in the composition of matter. This caused problems in trying to think through density.

> *Every single object has air in it but if the molecules are too small, but if the molecules are too close together, there won't be enough air to help it to float (inside of it), so that's why it sinks….. In between the molecules there's like little air but our eyes aren't good enough to see them and neither are microscopes. Only if you cut off a piece and you really had a good microscope and you looked real close into it and would see pockets.*
>
> - Detmar (CON)

> *I think its just like the molecules are spread out a little more and so it has more air space inside and is lighter. I think the air fills in the spaces where the molecules aren't."* - Sarah (CON)

The complexity of understanding air was a problem in explaining pressure as well.

> *I think the balloon deflated because the pressure rose as it dropped altitude. With more pressure, the air in the balloon is pushed together, leaving more empty space in the balloon.* - Torey (IFT)

> *"When there is more pressure on the outside it is getting pushed so, like, the push is making the air leak out…..You can't push in or it, like, pops, so it has to leak out.* - Detmar (CON)

It is clear in such explanations that students are thinking about air on a microscopic level as particles. This is also the level at which they introduce their understandings of speed and temperature.

> *As you rise higher into the sky you realize it gets colder. When the helium balloon rises, its molecules begin to cool and slow down. This makes the molecules move closer together causing the balloon to get smaller. The air around is also denser.* - Brad (IFT)

This explanation, taken from Brad's pre-unit inventory, is expressed only in terms of temperature, movement and density, things learned in the previous unit. He explains what happens in terms of pressure in his post unit inventory.

> *I believe the balloon will get bigger. As the atmosphere gets higher, the pressure becomes lower. Part of the reason why it gets lower is because the air is moving faster. The pressure inside the balloon is greater than the pressure of the air.*

He clearly thinks in terms of the pressure as a differential. However, when he tries to explain what causes the lower pressure, he returns to the idea of air in motion.

Although he doesn't say it, it seems that he, like many of his classmates is relying on Bernoulli's principle in his explanation. This means ignoring both the central idea of force as weight, which means there is less air pressure at higher altitudes, and his knowledge that air in higher altitudes is colder and therefore the particles slow down. The confusion results because he doesn't know how to coordinate the potency of the variables involved, and so he doesn't know which are relevant to the outcome and which are not.

Partial Understandings: Findings

The partiality of students' understandings showed up more clearly in longer explanations, where they were asked to extend their thinking. It was also more evident in the following questions:

- What causes liquid to go into your mouth when you suck through a straw?
- What causes wind?
- What do you think might cause the difference in density between a steel cylinder and a similar volume of steel wool?
- How does Galileo's thermometer work?

We noticed several concepts and ways of thinking that caused confusion across all topics. Things that can't be seen (the size, nature and bonding of atoms and molecules, properties of liquids and gases, air, water vapor and empty space) were hard to grasp, and students had difficulty deciding when to consider micro or macro levels. Wilensky and Resnick (1999) have written about the difficulty students have when reasoning at different levels in this way, and note that students have a difficult time coordinating micro-level and macro-level models. According to Perkins and Grotzer (2000), the level at which one analyzes a phenomenon often affects the details of the causality involved. This fits with previous research showing that non-obvious entities are difficult to reason about (e.g. Driver, Guesne & Tiberghien, 1985; Gelman & Kremer, 1991; Grotzer & Bell, 1999). The difficulty of understanding density as an intensive quantity has been written about extensively (e.g. Unger, 1991; Smith, Carey & Wiser, 1985). Many students were unsure of the relationship between mass, volume, and density, and when and how to use numbers, formulas, and laws. Several scientific concepts including heat, gravity, inertia were difficult. We found that students were unsure of how much heat it would take to cause chemical changes, and frequently thought that you could "add cold." Previous research has found similar patterns (e.g. Engel Clough & Driver, 1985). Understanding pressure as a pull and considering density primarily as a property caused problems. Students found it difficult to consider a system as a whole rather in terms of its elements, which caused them to neglect things that they actually knew. They also had trouble distinguishing the relative importance of various factors such as heat, movement, pressure, density, and directionality. Students most often considered a problem from one particular perspective. Often this was a general way they constructed all their understandings, at other times it seemed to a way of responding to a certain topic or questions. However, this had the effect of narrowing what students considered, and led to their missing the underlying causality.

Looking Across the Headings

An important feature of the use of headings in analysis is that data can be charted under multiple headings. Data that appears under more than one heading often reveals deeper patterns of thought and connection, of what students are paying attention to and relying on. This explanation was charted under both “static versus dynamic” and “concrete and bounded entities."

> *Right now I’m drawing the three causes of density. Right now I’m drawing the atomic mass of the compound, the object…This already has a larger mass than the aluminum because of the way the protons and neutrons line up and how many protons and neutrons it has …right now I’m drawing the atomic bonds and how they might relate to density. If the atomic bonds are stronger then more of them can fit into a space, if the atomic bonds are weaker, less of them can fit into a space…Now I’m drawing structure which is also part of the second cause of density. I’m trying to draw a crystal-like structure which may have to do with copper. Crystal-like structures seem to be stronger than regular or square-like structures for some reason.* Alex (CF)

As mentioned earlier, we found this to be static because he thinks of particles in terms of positions, bonds, and structure, and his language is exact and structured, which gives his explanation a sense of measured precision. We found it to be bounded through his reference to specific materials and the way he constructs his answer as a list of number of distinct causes and develops comparisons involving parallel language, and a sense of what is “regular." Overall we noted the complete, detailed, and graphic feel of his explanation.

On the other hand, this explanation was charted under "static versus dynamic" as a dynamic answer, and also under "self as model."

> *The things react in the heat because after a certain degree of heat the molecules have so great a density than water that they just sink to the bottom but when the heat isn’t affecting them yet, depending on ball and the color they are going to stay afloat until the heat affects them, so they‘re going to keep moving and have greater density…They react, like an animal, they react to the stimulus…* Christian (M+TTS)

Christian speaks about motion in terms of agency and describes heat as an affect rather than a source of energy. He describes sinking and floating in similar terms.

> *It determines its mass, almost automatically, for some reason. And if it’s lesser, it’s going to push it away from the center and if it’s the same it’s going to push it into the center and if it’s greater it’s going to push it down.*

Here, he describes water’s agency in sinking and floating in terms of active force.

Overall, we found that data often, but not always, overlapped between the static and bounded headings. Similarly, overlap was often found between dynamic and self-as-model thinking.   Formulaic definitions were often static and bounded, while those that involved force often showed agency. *"Inertia states that an object in motion wants to stay in motion"* Alex (CF). Experiential definitions more often involved dynamic and self-as-model thinking, while ones based on image could be either static or dynamic views. Explanations charted under partial understanding overlapped with all other headings: static and bounded models often missed the dynamic elements, complexity and range of factors involved. Dynamic explanations often lost the idea of relational causality, and self-as-model thinking tended to replace causality with affective reasoning.

The words clarity, certainty, and completeness came up across headings. Looking across the headings helped us to understand what our students thought of as "solidly scientific explanations" and the use of formulas, laws, a sense of diagram, step by step procedures, and numbers all supported this. At the same time, they used those things that made sense to them which often involved observations, and experiences, and involved personal perception, imagery and affective appeal. Finally, looking across the headings gave us a sense of the tension between the complexity of the situations students were trying to explain, and the need both to simplify them so they could be understood and to choose those factors that were most important in a particular situation.

Conclusions

Overall, this study indicates that, while teaching students about the nature of causality has been demonstrated to positively impact students' ability to restructure their knowledge and achieve scientific understandings, their explanations are also influenced by other factors that play active roles in what density and pressure mean to them. This resonates with findings by diSessa (1993) where he identified what he termed phenomenological primitives (p-prims) that were operated in specific contexts that elicited them and played a role in framing students' conceptions. While the factors identified here may be separate from their knowledge of causality, they shape students' overall understandings and may interact with their causal knowledge. We expect that the ways of structuring understanding described by our headings explain a portion of the variability found in our earlier studies, in the ways students use and transfer the underlying causalities that they are learning. The overlap between their different ways of thinking about science is most evident when children are asked to explain real world situations where they need to apply their understanding of the causality structures of density and pressure. In addition, the patterns that emerged as our headings seemed to have their greatest impact in how students thought about non-obvious elements such as molecules and air.

We found that using a phenomenological approach in conjunction with our empirical research provided additional and useful insights into how children understand science topics. Theories about science learning can be roughly divided into two approaches. One is that there are general patterns of scientific reasoning, and that as students learn these patterns, they develop skills that can be applied across topics (e.g. Chi, 1992; Kuhn, Amsel, & O'Loughlin, 1988). The other is that each topic has its own ontology, and that students need study each topic carefully in order to understand its structure (e.g. diSessa, 1993; Keil, 1986 We found that since students understand pressure as a force or density as an arrangement in space, their understandings of these topics relies on a body knowledge that is specific to each topic in a way that correlates with diSessa's p-prims (1993). However, our headings emerged from the data, and the way these headings held across students and across topics for a given student suggests that they bring general patterns that are applied across topics. Therefore, it seems likely that both theories play a valid role in scientific learning and deserve continuing research.

Implications for Further Research

This study reveals the importance of research into how learning various concepts impacts students' knowledge of other concepts. We found that in order to understand density and pressure, students used concepts of volume, mass, gravity, inertia, heat and force among others. How a student thinks about these, as well as how he or she understands atomic structure, empty space, states of matter, and the like seem to support or confuse their understanding of causality. We also found that in considering real world situations, students need to understand the relative importance of various factors; there is a need for additional research into how students choose the factors they pay attention to and ways to help them focus on the most important ones. It is also important to continue to take an in-depth look at how children change the ways they construct their explanations as they learn new concepts within a unit and across units. Finally, further research is needed into the impact of scientific and affective thinking on each other in the ways children construct meaning. These internal ways of structuring knowledge may affect both the transfer and the persistence of students' understandings of underlying causal structures.

Implications for curriculum

While this study gave us considerable insight into difficulties that students had in mastering science topics, and suggested teaching strategies that could counteract these problems, it is important to note that they are deeply rooted and not simple to teach to; much research over the last 25 years has been devoted to this issue. However, increasing our awareness of how students constructed their explanations certainly enables us to increase the effectiveness of our curricula. Since causal understanding is enhanced when a student can integrate elements of several models (for instance, combining static and dynamic elements), students need to become fluid enough with the models, formulas and laws they rely on to use them flexibly. Knowledge of concepts such as volume, area, mass, force and the properties of gases and liquids need to become practiced enough to provide a solid basis for building understandings of density and pressure. Curricula need to combine laws, formulas and facts with consideration of the variability and possibilities that exist in complex systems.

Students had trouble dealing with non-obvious factors. Students also need to become flexible enough in their thinking to understand when to rely on micro or macro levels of modeling, as well as to understand which model, formula or law gives the clearest understanding when. They need to develop several ways of considering force, and be given a chance to see how each affects their understanding of real-life situations. Consideration should be given to how best to introduce the notion of directionality, as force is a vector quantity. Confusion about air, in particular, which appears across the six headings of this study, indicates the need to give real attention to this factor. In studying the atmosphere, the relative importance of pressure, density, heat and speed of particle movement should all be considered in regards to questions being explored.

We found that, through careful analysis of a child's explanation, we began to hear his or her tacit questions. Students' own awareness of the partiality of their understanding, seen through their use of "might," "I think," "I guess," "I don't know," and similar phrases showed up in the interviews, much more than in the single question format of the inventories. Naturally, as both interviews and inventories are situations that ask them to construct answers, students may have avoided questions and expressions of uncertainty. However, teaching can and should involve helping students to notice and make explicit their own questions as a metacognitive tool.

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