

Using Metacognition to Facilitate the Transfer of Causal Models in Learning Density and Pressure

Sarah Mittlefehldt 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 Sarah_Mittlefehldt@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

Special thanks to Rich Carroll, Lucy Morris and Val Tobias and their students at Marshall Simonds Middle School in Burlington, MA for their participation on this study. We would also like to thank David Perkins and our colleagues at Project Zero and the Understandings of Consequence Project Team: Rebecca Lincoln, Gina Ritscher, Dorothy McGillivray, Becky DeVito, Sun Kim, as well as Pamela and Bill Mittlefehldt for their insight and support.

Using Metacognition to Facilitate the Transfer of Causal Models in Learning Density and Pressure

Sarah Mittlefehldt and Tina Grotzer, Harvard University

Introduction

Previous research on the Understandings of Consequence Project suggests that students tend to structure their experiences and understandings using default patterns of causal reasoning (e.g. Grotzer, 2002; Grotzer & Basca, in press; Perkins & Grotzer, 2000). Students are usually unaware of their assumptions about the nature of cause and effect and these patterns are typically not addressed by most science curriculum. The results of the first phase of the Understandings of Consequence Project suggested that engaging students in thoughtful reflection about cause and effect relationships in science can help students develop deeper understandings of fundamental concepts (e.g. Grotzer & Bell-Basca, 1999). During the second phase, which looks at transfer, one focus of the research explored the role of metacognition as a means to support the restructuring of students' ideas in science through the introduction and transfer of causal forms.

The primary focus of this paper is on the active regulation of one's cognitive processes in the transfer of learning causal structures in different scientific phenomena. To explore this dimension, we addressed the following questions: 1. Which metacognitive strategies did students show the most evidence of adopting when learning new concepts in science using complex causality? 2. In what ways did these metacognitive strategies appear to help students transfer their causal understanding between topics?

Theoretical Background

Many researchers (Blank, 2000; Georgiades, 2000; Hogan, 1999; Nickerson, Perkins, & Smith, 1985) have demonstrated the importance of mental management, or metacognition, as a means to support the restructuring of ideas in science or, in other terms, to facilitate conceptual change. Georgiades claims that "If conceptual change learning (CCL) is a chain-process of constructing new conceptions on pre-existing ones, then the durability of new conceptions, each time, should be seen as a prerequisite for effective learning (2000, p124)." In this sense, durability refers to the robustness of student's mental models. Georgiades argues that metacognitive activities may not only help facilitate transfer, but they may also support the durability of students' ideas in science. Other studies (Blank, 2000; Hogan, 1999) have reported similar findings, indicating that providing opportunities for students to formally reflect on their ideas may result in a more permanent restructuring their scientific conceptions. These results indicate that metacognition may help improve the transfer of causal structures when learning ideas in science.

Metacognition has been defined in a variety of ways and encompasses a variety of dimensions. For this paper, we used the particular characteristics of metacognition as defined by Hennessey. These characteristics are as follows:

- (1) An awareness of the content of one's own thinking.
- (2) An awareness of the content of one's conceptions.
- (3) An active monitoring of one's cognitive processes.
- (4) An attempt to regulate one's cognitive processes in relationship to further learning.
- (5) An application of a set of heuristics as an effective device for helping people organize their method of attack on problems in general (Hennessey, 1999).

In looking at the potential of metacognition to facilitate the transfer of causal understandings in the topic of density to that of pressure, this research is particularly interested in the latter two characteristics. That is, we are interested in exploring the mechanisms students use to manage their mental models in support of future learning and the reflective strategies they use to solve new problems.

The Metacognitive Learning Cycle model (MLC) developed by Blank (2000) describes formal opportunities for students to talk about their ideas in science class. Blank proposed that metacognition helps students to build stronger bridges between their science experiences, ideas, and understandings. Although Blank found that classes that used the MLC did not gain a greater pool of content knowledge, students in these classes were able to retain their restructured thinking longer. Because students were more mindful of the discussions and debates about the consideration of ideas, she concluded that the learning was more meaningful and therefore persistent (Blank, 2000).

Another important aspect of metacognition is how it works within group contexts. Hogan argues that the aim of education is not to develop an individual's personal knowledge structures, but rather to engage students in disciplinary knowledge that is open for debate and criticism (1999). Students learn as a result of information flows that occur within groups through communication processes and social structures, not solely as a result of neural connections within an individual mind (Hogan, 1999). Likewise, the development of metacognitive knowledge does not occur in a social vacuum. Students negotiate the status of their ideas in relation to other students or to universally held cultural assumptions on the way things work. For the research reported here, we looked at how metacognition was used by individuals as well as by groups to transfer causal understandings between topics.

Metacognitive Moves

The inquiry here is framed by three categories of metacognitive moves or techniques to help students use metacognition. Nickerson *et al.* (1985) refer to "metacognitive skills" as those strategic qualities that help thinkers acquire, use, and control both knowledge and other cognitive skills. The first category, adopted from Beeth (1998a), is "intelligibility" (see Table 1). It encompasses how students reflect abstractly on the content of their thinking. That is, when students ask themselves, "Does this make sense to me?" It is useful because it gives students a conceptual foundation in which to activate their

metacognitive processes. When assessing the intelligibility of a new idea, students may reflect on other students' ideas, their parents' ideas, or the teachers' ideas. They may ask themselves, "How does the way that this person thinks about the idea help me make sense of it?" In this way, intelligibility works on both an intra-personal as well as interpersonal level. That is, it works as self-reflection as well as reflection between individuals or small groups.

The second category of metacognitive tool is "wide-applicability." Employing this technique, students apply what they know about their thinking in one context to another. It involves connection making and looks at the role of reflection through experience. Students may ask themselves "How can this concept help me in other areas of my learning?" Or "What experiences (in class or outside of class) have I had that would help me make sense of this idea?" Georghiades (2000) makes an important distinction between transfer and applicability by stating that application is only part of the process of transfer. He defines transfer as the recognition of similarity of two contexts and application is the mental testing of potential solutions in attempt to apply the skill or conception to a new context. "Wide-applicability" is the metacognitive tool that a student might use to actually put into context a particular class experiment or "real world" experience that fits these relationships. From the relationship given between transfer and applicability, we begin to see the importance of wide-applicability as an important catalyst for transfer.

The third category, "plausibility," also adopted from Beeth (1998a), enables students to test their faith in a particular idea *vis-a-vis* alternative ideas. It is the realm in which students negotiate the status of their ideas. It encompasses the type of metacognition that occurs when students ask themselves, "Should I really believe this idea?" When testing the plausibility of an idea, students may seek counter-evidence against an idea. Students employing metacognitive techniques focused on plausibility are often very self-aware of their learning. As a result, they may question the learning and be skeptical of ideas that they only partially understand.

Another interesting component of metacognitive thinking focused on plausibility involves students' recognition of temporal changes in their own thinking. That is, when students say that they used to understand an idea one way, and after witnessing counter-evidence, they begin to think about the same idea in a different way. Often in this case, students' initial ideas may be held simultaneously with the negotiation of new understandings. In this sense, the student assesses their understanding of an idea by comparing their faith in their initial ideas weighed against the new and developing ideas.

Table 1: Metacognitive Moves: Context and Characteristic Questions

Metacognitive Moves	Context	Characteristic Questions
1. Intelligibility	Intra-Personal	Does this idea make sense to me? What part of this idea makes sense to me? What do I find difficult about this idea?
	Inter-Personal	What part of Ian's model makes sense to me? What might I add to have it make sense to me?
2. Wide-Applicability	Intra-Personal	How can this idea help me in other areas of my learning? Are there pieces of this idea that relate to other ideas I learned about? What are the fundamental ways in which they relate?
	Inter-Personal	How does Ian's model help me think about other ideas we've talked about?
3. Plausibility	Intra-Personal	Should I believe this idea? Does this idea seem likely to be true?
	Inter-Personal	Should I believe Ian's model? Even if it makes sense to me, is there something about it that seems unlikely to be true? What is believable about it?

Methods

Design

Students from six eighth grade science classes (n = 182) of two science teachers (three classes of each teacher) from a suburban school system in the Boston area participated in this phase of the research. The population of the school district was comprised primarily of lower to middle class families. Since earlier phases of the research indicated that using causal structures in learning science helped students develop deeper understandings (Grotzer, 2002), all six classes were given inquiry-based science curricula with a focus on using causal forms to deepen understanding. For example, the Density unit incorporated relational causality to explain how density differentials cause something to sink or float. In relational causality, the relationship between two things accounts for a certain outcome beyond the two things. Often it is a relationship of balance or imbalance or differential. Relational causality was also an important causal form taught in the Pressure unit. Similar to density differentials, using relational causality to think about pressure differentials enabled students to get a more complete picture of what causes lift, or what causes liquid to go into your mouth when you drink from a straw.

The six classes were divided into two intervention groups and a control group. Each group had two classes, one from each teacher. One group was given complete causal instruction in both units (density and pressure), but also received materials-supported transfer (MST). Another group was given complete causal instruction in all three units, received materials-supported transfer and also received teacher-supported transfer (MTST-all). The last group served as a partial control, receiving causal teaching and

materials-supported and teacher-supported transfer (MTST-Intro only) for density only and then received only causal teaching in pressure (see Table 2).

Table 2: Year 2 Intervention Conditions for Density and Pressure Units

Intervention Condition	Density Unit	Pressure Unit
Materials + Teacher Supported Transfer in All Units (MTST-All): Complete causal instruction with materials - based transfer support and teacher-guided transfer support.	Group 1 Group 2 Group 3 Group 4	Group 1 Group 2
Materials-Supported Transfer (MST): Complete causal instruction with materials -based transfer support (worksheets, videos, and activities outside of class).	Group 5 Group 6	Group 5 Group 6
Materials + Teacher Supported Transfer in first unit only (MTST-Intro Only): Complete causal teaching and materials-supported and teacher-supported transfer during the first unit, no supports added to facilitate transfer in other units.		Group 3 Group 4

All of the students were pre- and post-tested for their understanding before and after each unit. A subset of students (n = 18) was interviewed following each unit to assess their understanding of the concepts and as a measure of their metacognitive behavior. Class interactions were documented for later analysis of the metacognitive activity.

As additional background for interpreting data, daily field notes were taken to record observations on in-class dynamics, including metacognitive discussions, the general mindfulness of the class, and major distractions to the class. Explicit teacher-student as well as student-student discussions on the status of ideas and other spontaneous instances of metacognitive activity in class were also recorded on a daily basis. We also looked at students' writing samples to explore how students used metacognitive strategies to challenge their thinking.

Tasks

Good Science Thinking Moves

In all classes, students were introduced to "Good Science Thinking Moves." Posters were hung in both teachers' classrooms listed the following "Good Science Thinking Moves": (1) making connections, (2) questioning the learning, (3) self-reflection, (4) questioning the truth or believability of an idea, (5) comparing your idea with others' ideas. These moves encompassed different variations of intelligibility, wide-applicability, and plausibility. Teachers introduced these moves to each of their classes early in the first

unit (Density) and made periodic references to the posters as appropriate to the intervention conditions outlined above.

Students were taught to "make connections" by thinking of real world or in-class examples that fit what they learned. In making connections, they were also encouraged to compare new ideas to other things that they already knew. Making connections also helped students incorporate knowledge from other arenas of their learning to make sense of a particular concept in science class. Making connections primarily involves the metacognitive moves wide-applicability and intelligibility. That is, in practice, students make sense out of an idea by applying it within different contexts.

By questioning their learning, students were encouraged to be a bit skeptical and to think of counter-evidence that might refute the particular concept in question. In this way, through reflection, it was hoped that students would develop critical thinking skills that enabled them to gain a more complete picture of an idea. Similar to making connections, "questioning the learning" incorporated aspects of both intelligibility and wide-applicability. By thinking of counter-evidence and recognizing potential gaps in reasoning, students were encouraged to make sense of an idea by contextualizing information.

Self-reflection is a basic metacognitive thinking move. Students were urged to ask themselves, "Does this idea make sense to me? What part of the idea makes sense to me? What do I find difficult about this idea?" In this way, students were encouraged to use intelligibility to negotiate the status of their conceptions.

Students were encouraged to question the truth or believe-ability of an idea to help them negotiate its plausibility. Even if an idea makes perfect rational sense to a student, as a good science thinking move, questioning the Truth or believe-ability of an idea enabled students to probe their understanding to see if there is anything about the idea that seems unlikely to be true. It was hoped that this technique would help to reveal if there were certain fundamental barriers that challenge students from fully accepting a particular idea and to indicate what those hurdles might be.

The final "Good Science Thinking Move" that students were encouraged to use was comparing their ideas with others' ideas. In doing so, students asked themselves, how are other students making sense of this idea? How are other students' models similar or different from their own? In what ways do other models help them re-formulate their thinking? In this sense, students use wide-applicability and intelligibility as metacognitive moves.

Forms of Materials-Based Reflection

The teaching materials for the unit were infused with questions encouraging students to reflect upon their understanding. For example, one materials-based activity in density was given after being introduced to what causes differences in density at the microscopic level. Students were encouraged to think and write about whether or not what they had

learned made sense to them. They were also encouraged to test the plausibility and wide-applicability of microscopic level explanations for density in this activity (see Appendix A). In Pressure, one example of a materials-based activity to support metacognition involved having students reflect on their understanding after doing an experiment in class that helped them to think about how a straw works. In class, students engaged in a contest to see who could drink a standard amount of juice in the shortest amount of time using three different flask and straw set-ups. One flask had a regular straw in it. The second had a straw with a hole in it. The third flask had a straw through a stopper that created a seal with the flask. Before the contest began, students had drawn models to explain how they thought a straw worked. After engaging in the contest, they drew models of how the different straw set-ups worked. The materials-based reflective activity encouraged students to spend time thinking about differences between their initial models of how a straw worked with their later models, incorporating evidence that they witnessed during the contest. The activity also encouraged students to think about how they did or did not use relational causality to analyze what was going on. It also encouraged students to use intelligibility and wide-applicability to help them reason through their ideas (see Appendix B). For the materials-only groups, these reflections were not discussed as a class.

Forms of Teacher-Supported Reflection

The units also included explicit opportunities to engage in reflection that were teacher guided. For instance, while students were working on developing models in a group, their interactions were videotaped and in a subsequent class, students were asked to reflect on what thinking moves they were using and how the moves supported their developing understanding. An example of teacher-supported reflection in the density unit involved having students watch videotape of their own classroom engaged in a previous lesson. As they watched themselves discussing how objects (of different materials) with the same volume could have different masses, the teacher encouraged students to look for ways in which they used each other's ideas to make sense of the question. The teacher also encouraged students to consider the plausibility of ideas, and to connect ideas to other areas of learning (see Appendix C).

In the Pressure unit, one example of a teacher-supported reflection activity involved a group discussion on how causality might help to explain the theory of Boyle's Law. Boyle's Law states that at a constant temperature, as the volume of an enclosed gas increases, the pressure decreases. Students were asked to reflect on how relational causality in this context made sense to them and what they found confusing about the model. As a class, they also discussed the differences and similarities of each other's models, as facilitated by the teacher. Students were also asked how the use of relational causality in the context of Boyle's Law context compared to other examples they had thought about (see Appendix D).

Formal and Informal Assessment Tasks

To assess the use of metacognitive strategies in learning density and pressure, we used a number of qualitative methods. These methods included semi-structured interviews, class discussions, and samples of student writing. To analyze the effect of metacognition in supporting the potential transfer of causal structures between learning density and pressure and learning, in general, we compared individual and class use of metacognitive categories to students' scores from unit assessments taken before and after each unit. The assessments are as detailed in Grotzer, 2003 and repeated here.

Density Assessments

The density inventory was a written exercise consisting 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 often have in reasoning about density that results in misconceptions or alternative conceptions and that should relate to the structure of their causal reasoning (Grotzer, 2002). 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 and to explain each. The combination of questions provided students with opportunities to reveal that they understood the following: the relationship between mass and volume, the microscopic level of interaction, the material causes of density; that density is dynamic (as a result of changes in temperature and pressure), and that relational causality is 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. For instance, "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 and 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 and each focused on a certain phenomenon. Some of the sections followed up and elaborated on questions in the inventory. The interview was conducted as a structured clinical interview where students were asked a series of questions and then a standard set of follow-up probes were used. For instance, 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. Each interview lasted approximately 30 to 40 minutes. These interviews also formed the basis of measurements of students' use of metacognitive techniques on an intra-personal level as outlined below.

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 following: 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 explain 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 and tested with approximately 162 students and refined over the subsequent 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 questions in the inventory. As with the density interview, it 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. The final section offered scaffolded cueing of the causality involved where students were asked increasingly targeted questions about the nature of the causality involved. If they didn't spontaneously mention causality, 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?" As with the density interviews, these interviews also formed the basis of measurements of students' use of metacognitive techniques on an intra-personal level as outlined below.

Assessments of Classroom Interactions

As one means to reveal how students used the good science thinking moves, we encouraged the use of white boards to model and discuss their ideas and to reflect upon their thinking. These served as informal assessments and the sessions were videotaped for later analysis. Students began by drawing models of their own initial ideas allowing us to consider how students used metacognitive moves on an intra-personal level. Afterwards, they were encouraged to discuss their ideas with class members. The teacher prompted

critical debate by asking the class questions such as the following: “What makes sense to you about Ian's model?” “What do you think is confusing about Ian's model?” “Do you believe his model?” “How would you change Ian's model to have it make sense to you?” “How does his model help you think about other ideas we've learned about?”

General observations of classroom interactions were made in the form of field notes. Daily field notes were taken to record observations on in-class dynamics, including metacognitive discussions, the general mindfulness of the class, and major distractions to the class. Explicit teacher-student as well as student-student discussions on the status of ideas and other spontaneous instances of metacognitive activity in class were also recorded on a daily basis.

Samples of students’ writing were collected to provide additional informal assessments of how students used metacognitive strategies on an intra-personal level and whether they challenged themselves to think metacognitively, whether their reflections on their own thinking changed, and so forth.

Scoring

Metacognitive Measures

Each of the metacognitive measures (individual and class-based) were scored according to the following metacognitive categories. The following categories were developed after observing how students used the metacognitive moves in practice. We observed that metacognitive moves were rarely used in isolation. Students often used a combination of these metacognitive moves at different levels of sophistication. To look at how these metacognitive moves were used in practice as strategies for metacognitive reflection versus non-reflective explicit knowledge claims, we developed four categories of metacognitive and cognitive strategies. The purpose of the categories was to examine how the metacognitive moves of intelligibility, plausibility, and wide-applicability were used in the context of student learning (see Table 3). Notice that these categories are additive in the sense that category B includes the criteria for category A, category C includes A and B, and category D includes A, B, and C.

Table 3: Categories of Metacognitive Strategies

Category	Cognitive or Metacognitive Strategy
A	Explicit knowledge claim--cognitive statement
B	Explicit knowledge claim + reflective abstract reasoning (intelligibility)
C	Explicit knowledge claim + reflective abstract reasoning using "real world" models (intelligibility + wide-applicability)
D	Explicit knowledge claim + recognition and reflective exploration of the limitations of their own thinking using "real world" models (intelligibility + wide-applicability + plausibility)

Category A represents cognitive claims, or knowledge statements that were not reflective in nature. This type of thinking was explicit in the sense that a student clearly stated what he or she thought, without an awareness of the status of why they thought what they did. It did not fit our working definition of metacognition because it did not involve students' awareness of the content of their own thinking. Nor did it involve actively monitoring the students' own cognitive processes, or help students organize their thinking to manage future problems (Hennessey, 1999). An example of a student using category A was given in response to a question on the Density interview, "What do you think causes a hot air balloon to rise?" In response, the student stated, "I think that the hot air rises, forcing the hot air balloon to go up. Once it gets cold, it will start to sink (Subject #153)." In this example, the student did not reflect on the status of why they thought hot air causes the balloon to go up and why the cold air made the balloon sink.

Statements where students backed up their explicit knowledge claims by negotiating the intelligibility of the idea were scored as category B. This included statements where students considered if the idea that they stated truly makes sense to them by thinking it through on an abstract level. In a sense, this type of self-reflection is a fundamental level of metacognition. A teacher working with Beeth (2000) commented that by backing up knowledge claims with the use of intelligibility, or the overt discussion how an idea makes sense to students, they begin learning to think "both with their ideas and about their ideas (Beeth, 2000)." An example of a category B statement was given when a student was asked if two pieces of aluminum of different volumes have same density. The student responded, "They are both solid pieces of aluminum, but this one has a bigger volume. The other has a smaller volume. This one has a bigger mass. The other has a smaller mass. But I still think that volume for both of them would fit. It's kinda of like this...let's just say, for example that the volume is 4cm^3 [the larger piece] and the smaller-sized one is 2cm^3 . The mass of this [smaller one] is 1 gram. The mass of this [the larger] is 2 grams. The mass of both of them is distributed evenly. Therefore the density must be the same (Subject #73)." In this example, the student reasoned himself into understanding that the density of the two pieces of aluminum must be the same because of the outcome of his calculations based on the mathematical equation for density.

Category C combines the sense-making dimension of intelligibility with the connection-making aspect of wide-applicability. The essence of category C involves debating whether or not an idea made sense by placing the idea within a meaningful context. By connecting new ideas to familiar contexts, a student considered whether or not an idea makes sense to him or her. The following response to a question about a piece of steel wool and a solid piece of steel of the same volume was scored as Category C. The question was posed, "Do you think they have the same mass?" In response, the subject replied, "They used steel for a lot of buildings back before the 50s, so it would be stronger, so it would have to have a greater density to hold up all the weight. But I know that steel wool is sometimes used almost as sandpaper and so it would have to be light, because no one would want to have to carry something that is five or ten pounds across something. So I'd have to say that [solid] steel has a greater mass (Subject #70)." In this example, the student made a connection to the practical application of solid steel as a

construction material and the use of steel wool as a scouring pad. It was scored as Category C because the student considered whether or not the two objects had the same mass by thinking about their function in the real world--using both intelligibility and wide-applicability.

The final category, Category D, employed the use of all three metacognitive moves: intelligibility, plausibility, and wide-applicability. Accordingly, students used reflection to push their ideas by making connections and considering alternative explanations for an idea. Students were aware of the fact that they held two different theories to explain one idea. They may have talked their way through the idea, through abstract reasoning and connection making in attempts to determine which idea to believe. Students may also have recognized temporal differences in their thinking. That is, they may have recognized that they held different ideas at different times, perhaps before and after a particular discussion or class activity. For example, in the pressure interview, a student explained what pressure was and whether it could change in the following response:

In definition, pressure is just the amount of force put on an object. It's just the amount of force put on an object. Um, the mathematical equation is force divided by area, which would mean if you had 5 Newtons on say, the cassette holder. And that was say, 10 cm^2 or something. Then it would be .5 as the amount of Newtons per cm^2 . Other than the definition, the way I think of pressure--I think of in and out as one pressure, instead of having it as pressure one way or the other... I think that it can change. It all depends on where you are. Like, if you are on Mount Everest, the pressure is obviously going to be extremely low.... If you're at the bottom of the ocean... you'd have the air pushing down on the water, and you'd have all the water in the ocean pushing down on it, so it would be an extreme amount of pressure. And that's why scuba divers can only go so far... right at sea level, its like 15 lbs./in^2 What I would say it would roughly be, the max, even for the most almost super-human person who could endure so much, I think the max could only be like 19.5. 'Cuz if it's 15 lbs./in^2 , a square inch isn't that much, but the extra four lbs. multiplied by, who knows how much, it would be at least a thousand extra pounds on your body. That would mean that there would be a lot pushing out, which would make it really hard to comprehend. (Subject # 138).

In this example of a category D statement, the student began by providing different ways of thinking about defining pressure. In explaining alternative ways of explaining pressure besides the mathematical formula, the student talked about the "in and out" of pressure. In this sense, he picked up on the idea of pressure differentials as explained as a form of relational causality. By providing an additional definition of pressure besides the mathematical equation, he tested the limits of his understanding by expressing multiple lenses to view the problem (plausibility). He goes on to explain how pressure can change by applying his ideas about pressure in different contexts (wide-applicability). He also talked about pressure in higher and lower situations and the dynamics of how pressure changes between these two extremes. In this way, he tested the limits of his thinking by making connections.

Individual Use of Metacognition.

For each interview question, we recorded the number of each cognitive and/or metacognitive categories the student used. We then correlated the total number of categories used to students' posttest and overall gain scores on a unit assessment that

students took before and after each unit. For each individual metacognitive category, we also correlated the total metacognitive score with the post test score and the overall gain score on the unit assessment.

We also examined students' writing samples to assess how students used metacognitive strategies on an intra-personal level and considered the following questions: Did students challenge themselves to think metacognitively? How did students' reflections on their own thinking change? We coded instances where metacognitive statements were made.

Class Use of Metacognition.

To examine the use of metacognitive strategies in class, we looked at key class discussions around RECAST activities. Designed to "Reveal the Causal Structure" of an idea, these activities played a key role in exhibiting the strengths and weaknesses of students' understanding and application of causal structures. To explore how metacognition potentially helped facilitate the transfer of causal understanding, twenty-minute sections of discussion surrounding the same RECAST activity were videotaped and coded for the number of metacognitive strategies for each class. The same coding categories for the interviews (B, C, and D) were used for these class discussions.

Measures of Causal Understanding in Science Concepts

The inventories were scored using rubrics developed in an earlier phase of the project. Each rubric assessed students' ability to grasp the causal content in the context of the particular science concept. It assessed the level at which students grasped the structure of the concept. For example, on a question that asked about bringing a balloon from higher altitude to lower altitude, student responses were scored at the following levels:

Level 0- Student repeats question, gives a non-causal response, or elaborates on background variables

Level 1- Student attributes cause to obvious variables such as a hole in the balloon or that the air leaked out, or mentions pressure (or any other non-obvious variable) as a token explanation

Level 2- Student acknowledges a difference or change in pressure but does not elaborate, or uses non-obvious variables other than pressure, such as temperature

Level 3- Student focuses on one side of the pressure differential/ equation only

Level 4- Student mentions both sides of the pressure differential/ equation but does not acknowledge their interaction

Level 5- Students implicitly or explicitly acknowledges the pressure differential/ equation and interaction

The scoring rubrics are further elaborated in Grotzer, 2003.

Results

For this subset, no significant differences were found between teacher-supported groups and non-teacher-supported groups. Because these interventions are part of a larger study across five science topics, it is premature to draw any conclusions about the efficacy of

the interventions in the broader context. However, for the purposes here, these conditions were collapsed for the remaining analyses.

The analysis first considered in the broadest sense whether or not students experienced gains from pre- to post-test on density and the relationship between potential gains and scores on the metacognitive measures. A paired t-test revealed significant pre- to post-interview differences ($t(17) = -7.56, p < .0001$), explaining 49% on the variance in scores. The measure counting the total number of metacognitive statements that students made in the post-interview for density was a significant predictor of density post-test score ($t(17) = -11.41, p < .0001$), accounting for 34 % of the variance. These variables were entered into a multiple regression analysis. Together they explain 63% of the variance in scores. Both were significant predictors ($F(1, 18) = 12.19, p = .0033$) and ($F(2, 18) = 6.03, p = .0268$) for density pretest score and metacognitive score, respectively. Figure 1 details the parameter estimates.

Figure 1.
Prediction Formula Detailing Parameter Estimates (Density Pretest Scores and Metacognitive Scores) to Estimate Pressure Post-test Scores

$$\text{Intercept} = -0.67 + \left\{ + 1.07 \times \text{Density Pretest Score} \right\} + \left\{ + 1.24 \times \text{Metacognitive Score on Density} \right\}$$

While the post-test scores measure how well students understood density in terms of the explicit causal challenges as well as more generally, another measure of how well students did on the post assessments deals with how many of their post-test responses were structured by relational causality. Students' performance improved significantly from pre- to post-test, ($t(17) = -4.97, p < .0001$) with means of .67 ($SD = .59$) and 1.55 ($SD = .70$), respectively. However, pre-test scores were not a significant predictor of post-test scores, ($F(1, 18) = 1.92, p = .18$) explaining little of the variance ($R^2 = .10$). Metacognitive score on density was a significant predictor ($F(1, 18) = 5.03, p = .04$) explaining 24 % of the variance (Density Relational Model Score = $0.49 + 0.11 \times \text{Total Metacognitive Density Score}$).

Next, the analysis aimed to establish whether or not students transferred these gains to their understanding of pressure and how metacognition may or may not have interacted with their ability to do so. A regression analysis revealed density post-test score to be a significant predictor of pressure post-test scores ($F(1, 17) = 6.10, p = .03$) explaining 29

% of the variance. Of the 18 students in the subset, all but two had at least one relational model on the density post-test. Of these, only one student did not show a relational model on the pressure post-test. Metacognitive performance on the density post-interview was a significant predictor of whether or not students transferred the models as defined above ($F(1, 15) = 4.73, p = .05$) explaining 27% of the variance (Transfer Score = $0.23 + 0.06 \times$ Total Metacognitive Density Score). Class Metacognitive Scores did not predict whether students in this subset transferred the models or not ($F(1, 15) = .38, p = .54$) explaining almost none of the variance in scores. We defined transfer of the relational model in the following way. Students had to detect at least one relational model on a density post-test to reveal that they learned the base concept. Then they had to show understanding of at least two of the possible three relational models on the Pressure post-test to show that they had transferred it to the target.

Next, the analysis looked at a finer level of grain to consider the question, "Which strategies did students show the most evidence of adopting when learning new concepts in science using complex causality?" We found that students employ a diverse range of metacognitive strategies. In the interviews, the most frequently used strategy was Category B, explicit knowledge claim plus abstract reasoning to think through a particular idea. We found that higher scores of category B correlated to overall post-test scores ($r = .25, p = .03$). Yet, during classroom discussions, we found that Category D, exploring the limits of students' ideas using all three levels of metacognition (intelligibility, plausibility, and wide-applicability), surfaced the most frequently in both classrooms. Of the total metacognitive strategies used in both classes, Category D was used 42.0% of the time, while categories B was used 28.4% of the time and Category C was used 29.6% of the time.

The following Category D statement shows a typical pattern in students' thinking, that is, the recognition of changes over time in his or her thinking. For example, when asked, "What's going on when density changes?" a student relied, "Well, I thought at first that it was kind of like a chemical change. It can be changed chemically, I think, but a physical change can also be done like compacting bread or pouring something in [to make it a mixed density] (Subject #112)." Compacting bread was an activity performed in class to demonstrate that the density of bread can change when you compress a full loaf of bread to half its volume. Since you change the volume without changing the mass, the density increases. The student also participated in activities in which salt was poured into a box of marbles. As the spaces between the marbles were filled, the density of the box increased. Before doing these activities, this student thought that density could only change via a chemical change. After doing the experiment, the student noticed how her thinking changed and she was able to recognize the emergence of her new understanding.

At the end of the Pressure interviews, students were asked to note any metacognitive strategies that were particularly useful to them from a list of "good science thinking moves" (see Appendix E). Students' responses indicated that comparing their ideas with other students' ideas and making connections to other areas of their learning were the most useful. The results of this self-assessment were consistent with our findings from the clinical interviews. That is, we found that higher scores of category C (intelligibility +

wide-applicability) correlated with higher overall gain scores ($r = .27$, $p = .03$). This supports the notion that students learn effectively by comparing their ideas to other students' ideas. It also supports the claim that connecting new ideas to familiar contexts helps students understand learning objectives. An example of this was provided at the end of a Pressure interview, when a student was asked if she wanted to add anything before they concluded the interview. She volunteered the following:

Well, if you're thinking about doing stuff for next year, keep doing the experiments, like different variations of experiments. I remember how we were doing the balloon over the flask we did it in two different ways, getting the balloon in and getting the balloon out and that helped because you have to reverse your thinking and think about it in different ways. The more experiments you do, it's easier to connect things like concepts. And it's easier to believe it, once you see it. I think I'm more of a visual learner. If I see it, I can believe it more and comprehend it better. And I guess that helped a lot because a lot of times in science you can't explain a lot of things because they're just too hard. And you can't, like, visually show them. It's easier when you have an experiment and you have to reflect on it too. Like, what you understand about it and what you don't 'cuz it helps you to get a better understanding and learn more. And the practical application, like how we had to answer those questions about... like, why are runways longer in Denver and San Francisco? It made you practically think about it. So it's not just like some topic you learn in school because you can like really apply it to the world. And, like, the airplanes, I never really realized how the difference in pressure above the wing and below the wing gave it like the plane lift. I never really thought of it that way. But now I can apply it and realize that's how the plane works and it makes more sense too because it's connected to something. (Subject # 150).

In this example, the student shows a sophisticated understanding of what's useful to her in her own learning. Connection-making as well as self-reflection are clearly important metacognitive moves in her learning.

In addition to addressing which strategies students showed the most evidence of adopting when learning new concepts in science using complex causality, a goal of this paper is to explore the ways in which these metacognitive strategies appeared to help students transfer their causal understanding between topics. In addressing this second piece, we found many examples where students who made more metacognitive statements in the course of their interviews were also more likely to map the relevant analogical relationships when transferring concepts. As seen in class discussion, this is not to imply that they necessarily did so quickly and easily. Often students talked through how the two concepts mapped on to each other, considering and rejecting mappings that did not work along the way. Often multiple metacognitive strategies were utilized simultaneously, making connections as evidence to make sense of an idea, rather than purely abstract connection making. However, by the end of the interview, they often effectively mapped the relationships and used the similarities to reason about both the base concept and the target concept. For example, while discussing the question, "What causes the liquid to go into your mouth when you drink from a straw?" the interviewer asked if the student could consider how relational causality might help her to think about this question. This student received explicit instruction in relational causality in the Density, but not in the Pressure unit. In response, the student replied:

You know, like in English how a complex sentence has one independent clause and one dependant clause? That's kind of what relational causality is like... If you don't have the independent clause, then you don't have the complete sentence. [Linear causality] is just something that happens. It

doesn't depend on anything else to happen. Two things are not related in any way. They're very independent, like a compound sentence.

So wait yeah, actually, in a way, it is because this liquid going up happens because there is a lower pressure here [pointing to inside the straw]. This happens because of the low pressure. If the pressure were equal, nothing would happen because this would be pushing down just as much as this would be pushing up. So, like in a way it is relation.

Interviewer: You're thinking of "relation" in terms of what relationship?

The two pressures. ... It's like, when you see a cup on a table with a straw, its not like the liquid is going up by itself because nothing is happening to cause it to do that. (Subject #507).

In the text reported here, the student actively reflected on what she had already learned about relational causality in a previous unit. She uses the third metacognitive tool: "wide-applicability" to think about relational causality in a context that makes sense to her. She compared it to the form of English sentence structure. By providing the terminology of "relational causality" the interviewer provided a slight cue and the student was able to apply her understanding of relational causality in the context of density to discuss how pressure differentials work to cause liquids to move up a straw.

Another example comes from an interview in which the same question was posed: "What causes the liquid to go into your mouth when you drink from a straw." In this case, the student began his answer by focusing on the expansion of your lungs to create space for air to enter. In this sense, his initial idea exemplified linear causality. But as he continued to reason through his idea, he realized that there was a gap in his reasoning. He began by stating:

As your lungs expand, it causes more and more air to be pushed into your lungs and then the water goes up. And obviously the water doesn't go into your lungs, so somehow your body regulates it so the water goes down to your stomach.

Interviewer: Why would expanding your lungs change the pressure?

Um, the reason would be because as it forces the air to expand...because air goes into them as they expand, there shouldn't be any empty space in your lung. So the air expands, then more air rushes in to fill up those empty spaces, which causes it to get dense and to equalize. And then water moves up. And then your lungs expand even more, which would force the liquid up farther. And then the air would expand. The air would become, there'd be more air in your lungs, which would make it more dense.... That's about it. I'm trying...I know that wasn't it. To me, that wasn't a good ending, I really didn't finish it off. I'm trying to think of what I missed....

Oh! And then the outside pressure would force the water down. And then up the straw because the inside pressure of the straw is less and the pressure around the area, around the surface of the water is more, so it goes down. And because it obviously doesn't go through the glass, it forces it up. (Subject #138).

In this example, the student recognized that his idea was incomplete. His pause to reflect on why the idea was incomplete enabled him to develop a more relational understanding of the difference between the higher outside air pressure pushing down on the liquid and the lower pressure created inside the straw when you suck on it. It is this difference and

the relationship between the two pressures that shows a deeper understanding of how a straw works.

The following exchange ensued in a classroom where the teacher explicitly facilitated a conversation about how relational causality helped students in revising their models of how a straw worked before and after the three flasks experiment as described in the "Forms of Teacher Supported Reflection" section.

Subject #100: I might have subconsciously made the connection. I knew what was happening—like, I knew one thing would affect the other, but I didn't go the extra step to put two and two together to get that it's relational causality... I would say it [relational causality] did really help because I understood what was going on and how one could change the other. By throwing in relational causality it would kind of change what I was thinking about originally. Like, I guess I thought it was more or less a "Domino thing," that one thing would make the next happen in a chain, like that. But if you think about it as a relational causality, then you would have to change your idea from one thing to causing the next to happen, then the keep on causing the next thing to happen...to that both go together to make one thing happen. Like, as you lessen the air pressure in the straw, the greater air pressure outside can force down, that makes the liquid able to rise up the straw. One thing starts the next.

Teacher: So can you say how you're thinking about it now?

Subject #100: Well, like if both affect each other, then it's because that the air pressure in the straw lessening and the air pressure outside staying the same, the lesser air pressure inside and the greater air pressure outside causes the liquid to go up the straw."

Subject #112: I don't think its really like domino causality because we saw the two causes are high air pressure outside and no air pressure inside, but we already saw that with Mary's straw, there wasn't any air pressure. And she took out the air pressure from the inside the air pressure, but it didn't cause it to go up right away. It needs the other...

Subject #106: Originally, I knew pressure was involved, but I never really thought of it as a relationship between high and low pressure. And to get the pressure itself is another relationship between force and area. And you can break it down and see how it works.

This conversation of this class clearly illustrates a culture of reflective thinking. In this example, we see student using all three metacognitive moves, that is, intelligibility, wide-applicability and plausibility. All three students interviewed from this class, despite different achievement levels, had two relational models on the density post-tests (out of two possible relational questions). All three interviewees also had at least two relational models on the pressure post-test (out of three possible relational questions). Thus, all three interviewed students from this particular class met the criteria of how we defined transfer for this study. Such metacognitive activity in class may support individual reflective thinking and deep learning.

Discussion

We attribute our findings to two distinct phenomena: 1) Students who considered the plausibility of their ideas through the negotiation of whether or not their own notions of causality made sense to them were able to gain a deeper understanding of the particular causal form; 2) Students who were able to reflect on their thinking were able to

understand the forms of causality as independent, abstracted concepts more clearly. This ability to abstract the key structures supported their ability to apply the structure flexibly to new concepts. Thus, generally speaking, students engaged in metacognitive activities seemed more likely to transfer their understanding of causal structures between topics than those students who were not engaged in metacognitive activities. Again, it is important to note that our findings are based on correlational tests and qualitative data. An explicit experimental intervention to isolate the effects of metacognitive moves to help students transfer causal structures between topics in science would be interesting direction for future research.

The research reported here indicates that metacognition may play an important role in the transfer of causal models between topics in science. Questions to consider for future research involve the most effective forms of metacognition and to what degree does metacognitive activity need to be supported by outside sources. Our findings also support the notion that when learning within group contexts, students are more likely to test the limitations of their ideas by using a broader range of metacognitive strategies than they tend to use when they individually reflect on their thinking. This may also indicate that when introducing students to new ideas, teachers find it helpful to use multiple metacognitive strategies to engage students in reflecting on their thinking. Students' preference to use category C, intelligibility and wide-applicability, may also support the notion that connecting new ideas to familiar contexts helps students understand learning objectives. It may also support the claim that students learn effectively by comparing their ideas to other students' models. This establishes another interesting direction for future research. That is, what is the most effective type of reflective connection making? Is it to lab experience, "real world" experience, or to the models and ideas of others? Another direction for future research addresses the question of how metacognition works within groups. That is, how does collaborative metacognition inform and deepen students' learning? What is the role of the teacher in facilitating metacognition versus the internal dynamics of particular groups? Identifying strategies to facilitate reflective classroom cultures may help abstract concepts such as causality become more accessible to students. Building metacognitive classrooms may also help to enable the transfer of causal models between topics.

References

- Basca, B. & Grotzer, T.A. (2001, April). *Focusing on the nature of causality in a unit on pressure: How does it affect students understanding?* Paper presented at the Annual Meeting of the American Educational Research Association, Seattle, WA, April 10-14.
- Beeth, M.E. (1998a). Teaching for conceptual change: Using status as a metacognitive tool. *Science Education*, 82 (3), 343-356.
- Beeth, M.E. (1998b). Facilitating conceptual change learning: The need for teachers to support metacognition, *Journal of Science Teacher Education*, 9(1), 49-61.
- Blank, L.M. (2000). A metacognitive learning cycle: A better warranty for student understanding? *Science Education*, 84(4), 486-516.
- Georghiades, P. (2000). Beyond conceptual change learning in science education: focusing on transfer, durability and metacognition. *Educational Research*, 42 (2), 119-139.
- Grotzer, T.A. (2002). Expanding our vision for educational technology: Procedural, conceptual, and structural knowledge. *Educational Technology*, March-April, 52-59.
- Grotzer, T.A. (2003). *Transferring structural knowledge about the nature of causality: An empirical test of three levels of transfer.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching. Philadelphia, PA.
- Grotzer, T.A., & Basca, B.B. (in press). Helping students to grasp the underlying causal structures when learning about ecosystems: How does it impact understanding? *Journal of Biological Education*.
- Hennessey, M.G. (1999). Probing the dimensions of metacognition: Implications for conceptual change teaching-learning. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching. Boston, MA.
- Hogan, K. (1999). Thinking aloud together: A test of an intervention to foster students' collaborative scientific reasoning. *Journal of Research in Science Teaching*, 36 (10), 1085-1109.
- Nickerson, R.S., Perkins, D. N., and Smith, E.E. (1985). *The teaching of thinking.* Hillsdale, New Jersey: Lawrence Erlbaum Associates.
- Perkins, D.N. & Grotzer, T.A. (2000, April). *Models and moves: Focusing on dimensions of causal complexity to achieve deeper scientific understanding.* Paper presented at the annual conference of the American Educational Research Association, New Orleans.
- Smith, C., Carey, S., & Wiser, M., (1985). On differentiation: A case study of the concepts of size, weight, and density. *Cognition*, 21, 177-237.
- Smith, C., Grosslight, L., Davis, H., Maclin, D., Unger, C., Snir, J., & Raz, G. (1994). *Archimedes and beyond: Helping students to construct an understanding of density and matter.* Educational Technology Center, Harvard University: Cambridge, MA.
- Smith, C., Maclin, D., Grosslight, L., & Davis, H. (1997). Teaching for understanding: A study of students' preinstruction theories of matter and a comparison of the

effectiveness of two approaches to teaching about matter and density. *Cognition and Instruction*, 15(30) 317-393.

Tishman, S., Perkins D. N., & Jay, E. (1995). *The thinking classroom: Learning and teaching in a culture of thinking*. Allyn and Bacon, Boston, MA.

Appendix A:

Example of Materials-based Metacognitive Activity in Density

Reflecting on What You've Learned about Changes in Density

In the past few classes, we have considered what causes differences in density at the microscopic level and how density can change. For homework, please answer the following questions. Use the back of this sheet if you need additional space.

1. Of what you've learned about what causes differences in density, what makes sense to you? Are there any pieces of what you've learned that seem especially clear to you? What about it makes it easy to understand?
2. Of what you've learned about what causes differences in density, what doesn't make sense to you? What pieces seem especially difficult to understand? What about them makes them difficult?
3. Sometimes even when we understand an idea, we may not believe it. Comprehending an idea is not the same thing as believing it to be true. In terms of density, is there anything that you believe to be true? Why do you believe it to be true?
4. Is there anything that you believe is not true? Why do you believe it is not true?
5. Is there anything about what you learned about density that relates to other ideas you may have learned about? What are they? In what ways do they relate?

Appendix B:
Example of Materials-based Metacognitive Activity in Pressure

Reflecting on Understanding and Making Connections

Before engaging in the drinking from a straw activity in class today, we drew models of how we thought straws worked. After engaging in the contest, we drew models of how the different straw set-ups worked. Now you should spend some time thinking about your models. Ask yourself and answer the following questions:

1. What differences do you notice between your beginning models and your later models?
2. Did you use relational causality to analyze what is going on? If so, explain how it helped you think about what is going on and explain any relational aspects of the different models. If not, explain how it didn't help you think about your models.
3. Did any of their explanations become increasingly complex in terms of the numbers of relationships that they were explaining?
4. Is there anything about this experiment that does not make sense to you?
5. Is there anything else that you've learned about before that helped you understand this activity?

Appendix C:
Example of Teacher-Supported Metacognitive Activity in Density

Reflecting on our Thinking as a Group

The more we can begin to understand our own thinking, the better we understand and process ideas in science. As an exercise to help us reflect on our thinking, as individuals and as a group, we will watch a video from yesterday's lesson. As you watch the video, look for ways in which you use each other to make sense of ideas, to consider the plausibility of ideas, and to connect ideas to other areas of learning. Here is a list of possible situations to look for:

Instances where...

- ?? When talking about his or her model, a student explains what makes sense to him/her. The student may explain why certain any pieces are particularly clear and easy for him/her to understand. He or she may also talk about things that still seem unclear about an idea.
- ?? After one student shares his/her response, other students understand the original student's model, they may understand parts of the model, or they may not understand the model at all.
- ?? Students discuss their different understandings. After one student shares his or her model, other students in the class add to the first student's model to have the idea make sense to them.
- ?? Students talk about whether or not they believe a particular model. Sometimes even if a model makes sense, you may not necessarily believe it. Can you recognize any examples when a student (or a group of students) talks about "getting" a particular model, but not necessarily "buying" it? In other words, instances when students debate whether or not an idea is true?
- ?? In the discussions, were there any instances when students referred to common experiences that you, as a class, have shared (or maybe not shared) that made thinking about this idea difficult to understand?
- ?? Were there any common experiences or understandings that the class shares that helped class members make connections about this idea to other areas of learning? Was there any common theme that students tended to refer to when explaining their ideas?

Appendix D:

Example of Teacher-Supported Metacognitive Activity in Pressure

Reflecting on Causality

Discuss the following questions as a group in class. If there is time, record your thoughts.

1. How does using a relational causal model help me to make sense of Boyle's Law?
2. Is there anything about Boyle's Law and/or relational causality that doesn't make sense to me?
3. What is difficult about thinking about Boyle's Law using relational causality?
4. Do other students seem to have similar understandings of relational causality in this case? How do other students' ideas compare to mine? How are they similar? How are they different?
5. Can I think of other examples of Boyle's Law in action? How might I explain these other examples using relational causality?
6. Can I think of counter-examples that seem to disprove Boyle's Law? Are there any conditions in which Boyle's Law does not work?
7. What do I need to be aware of when applying Boyle's Law?

8. How does the use of relational causality compare to other examples you've thought about? That is, how is it similar to other examples? How is it different?

Appendix E: Good Science Thinking Moves Checklist

Good Science Thinking Moves:

Only check off ones you used at least once. It's fine if you used none. We want to know if these moves were helpful, maybe they were, maybe they weren't. Your responses will help us decide whether it is a good idea to include them in science curriculum.

_____ **Making Connections:**

Thinking of examples that fit what you learned or comparing it to other things that you know. Asking yourself, how can this idea help me in other areas of my learning?

_____ **Questioning the learning--being a bit skeptical:**

Thinking of examples and counter-evidence that didn't fit what you learned.

_____ **Self-Reflection:**

Asking yourself, does this make sense to me? What part of this idea makes sense to me? What do I find difficult about this idea?

_____ **Questioning the Truth of Believe-ability of an idea:**

Even if it does make sense to you, do you believe this idea? Is there something about it that seems unlikely to be true? What is believable about it?

_____ **Comparing your ideas with others' ideas:**

Asking yourself, how are the other students making sense of it? Do they think of it differently than me or similarly?