

Transferring Structural Knowledge about the Nature of Causality:  
An Empirical Test of Three Levels of Transfer

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# Transferring Structural Knowledge about the Nature of Causality: An Empirical Test of Three Levels of Transfer

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## *Introduction*

Scientifically accepted explanations often require students to structure knowledge in ways that contradict their expectations about the nature of how causes and effects behave. 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). Students who were exposed to activities designed to reveal the underlying causality of the topic and who engaged in discussion of the underlying causality outperformed students who participated in the same units minus those features. This was so across a range of topics, including electricity, ecosystems, density, and air pressure, and across a range of ages from third grade through 11<sup>th</sup> grade (see e.g. Perkins & Grotzer, 2000; Grotzer, 2000; Grotzer & Basca, in press).

However, even if students demonstrate understanding of the causal structures and subsequently deeper understanding of the scientific concepts within the context in which they are taught, can students transfer their understanding to new topics? The question of students' ability to transfer causal knowledge bears on whether such learning has reach beyond the immediate contexts in which it is taught or if it supports learning of new concepts. This paper reports on an investigation to study whether transfer occurred 1) between isomorphic concepts; 2) between nonisomorphic concepts; and 3) more generally, as preparation for future learning as defined by Bransford and Schwartz (1999). This paper is part of a set of three papers. The second paper (Mittlefehdt & Grotzer, 2003) looks at the extent to which students engaged in metacognitive behaviors in relation to their ability to transfer the causal structures. The third paper (Ritscher, Lincoln, & Grotzer, 2003) takes an in-depth look at transfer between density and pressure concepts and considers how the ways that students construed meaning either hampered or facilitated their success in transferring the causal structures that they were learning.

## *Theoretical Framework*

### Learning How to Structure Causality

A growing body of research suggests that students hold limited notions about the nature of cause and effect (e.g. Chi, 2000; Driver, Guesne, & Tiberghien, 1985; Perkins & Grotzer, 2000; Wilensky & Resnick, 1999). Grotzer and Bell (1999) outlined tendencies in student thinking that lead to such limited notions. To name a few, students expect obvious causes and obvious effects, missing effects that involve systems in equilibrium or those that involve "passive" agents. They detect local causes and local effects but fail to recognize action at a spatial or temporal distance (Spelke, Phillips, & Woodward, 1996). They assume simple linear, sequential causal patterns with temporal priority between causes and effects (Bullock, Baillargeon, & Gelman, 1982).

Without the necessary expert structural knowledge (which may depart from our typical defaults) and a reflective sense of where it applies, students risk imposing limiting structures on new information. This results in distorting understandings to fit a typically less complex structure (e.g.

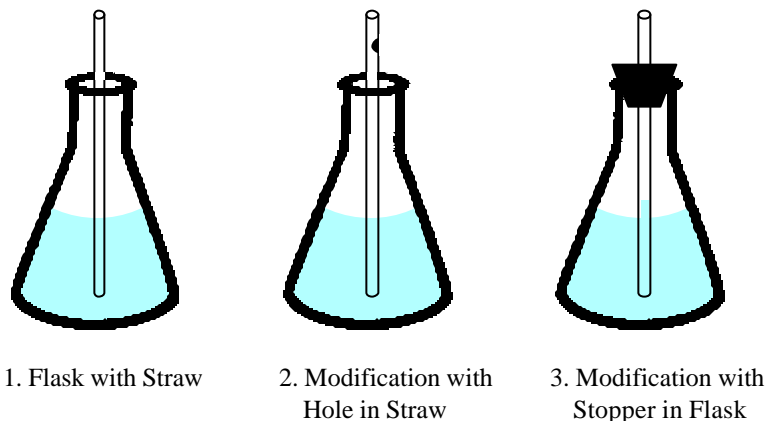
Grotzer, 2000; Slotta & Chi, 1999; Wilensky & Resnick, 1999). Students need opportunities to learn how to structure new knowledge as well as the opportunity to develop a reflective stance on how they structure understanding so that they actively consider and revise the structures that they engage (e.g. Basca & Grotzer, 2000; Zohar, in press).

Our earlier research sought to identify and impact the ways that students structured the underlying causality in science concepts. We sought to broaden students' repertoire of causal models so that they had more sophisticated knowledge about how causes and effects behave. We engaged students in units that included activities designed to REveal the underlying CAusal STRUCTure or RECAST activities and discussion about the nature of causality. What do RECAST activities look like? Here are some examples from the Pressure Unit. In relational causality, the relationship between two things accounts for the outcome. Often it is a relationship of balance or imbalance (differential). In one activity, students are asked to come up with models to explain what is happening when a balloon is put inside a bell jar, the air pressure inside the jar is lowered and the balloon expands. Students write their explanations for the balloon's expansion in size and discuss their ideas. In order to explain what happens, students need to think about the pressure differentials in play--a relational causality.

Another activity attempts to help students understand the relational causality involved in drinking from a straw. Typically, students interpret what happens when you suck on a straw in terms of simple linear causality such as, "sucking pulls the liquid up the straw." In order to reveal that a pressure differential, a relational causality, is in play, students are given three different flasks, each half-filled with liquid with a straw inserted, and are asked to see who can drink the liquid the fastest. Two of the flask/straw systems have various modifications that prevent the formation of a pressure differential. One has a hole in the straw above the height of the liquid that enables the lower pressure inside the straw to be equalized with the outside air pressure, thus preventing the formation of a pressure differential. The other has a stopper at the top that is sealed tightly around the rim with a hole that exactly fits the size of the straw. When the student tries to drink from it, some liquid rises up the straw, lowering the air pressure inside the flask to match the lowered air pressure in the straw, making it nearly impossible to drink any more liquid. (This activity was adapted from one by Liem (1992.)) These causally-focused activities reveal that something other than linear causality is involved and offer insights into the nature of that causality. Students discuss why the causes and effects of air pressure are often hard to notice and how this can lead to linear models of cause in pressure-related situations.

Figure 1.

Illustration of Straw-Flask RECAST Activity



Across most topics, we found support for the value of engaging students in RECAST activities (e.g. Bell-Basca, Grotzer, Donis, & Shaw, 2000; Grotzer, 2000). In some topics, density for example, the results are not as dramatic as on some others, electrical circuits, for example. It appears that the pattern of causality involved in density may be less counterintuitive to students than those in electricity such that some of them are able to glean it from instruction that does not specifically focus on it. The sum of the previous studies offers support for the hypothesis that teaching students about the structure of the nature of causality improves their ability to reason about topics for which they typically have misconceptions.

### Transferring Causal Understandings

The research reported here investigated whether students' understanding of the underlying causal structures remains wedded to the context in which it was taught or whether it transfers to new learning. The current investigation (the first phase of a larger study) asked, "How well does learning about causal structures in one topic transfer to other topics without formal shepherding of the transfer process?" In asking this question, we understood that the odds were against the likelihood of transfer. A rich research literature shows that even when students are able to demonstrate mastery of certain skills, they are unlikely to transfer these skills to new areas of learning on their own (e.g. Brown, 1989; Gick & Holyoak, 1980, 1983; Holyoak, Junn & Billman, 1984; Perfetto, Bransford, & Franks, 1983) and that scaffolding is needed to help students transfer the concepts (e.g. Bransford, Arbtiman, Stein, & Vye, 1985; Perkins 1989; Perkins, Farady, & Bushey, 1991). Students typically need help "bridging" or making outreaching connections to the new material (Perkins & Salomon, 1988).

Three levels of transfer were explored: 1) traditional "near" transfer which translates here as, "Does learning about specific forms of causality in the context of one science concept make it easier for students to learn about that specific form of causality in another context (in the service of deeper learning of the new science concept?)" 2) traditional "far" transfer which translates here as, "Does learning about specific forms of causality in one context make it easier for students to learn other forms of causality (in the service of deeper learning of the science concepts?)" and 3) "Preparation for Future Learning Transfer" as defined by Bransford and Schwartz (1999) which translates here as "Does focusing on issues related to the nature of causality when learning science concepts impact students' ability to learn science concepts in the future?" This level considers whether students become more aware of the role of causality in science concepts such that they apply this awareness to future learning.

The first level of transfer—between isomorphic concepts—asks about whether or not students can map an analogical causal form from one science context to another. According to Gentner's structural mapping theory (1983), relational mapping is a key aspect of analogical reasoning. Relational similarities between the base problems and the target problems allow the target problem to be solved by analogy to the base. Evidence drawn from across a variety of research traditions supports that learners of all ages are capable of learning through analogy (Brown, 1989; Brown & Kane, 1988; Gentner, 1977, 1988, 1989; Goswami, 1991, Goswami & Brown, 1989; Johnson & Pascaul-Leone, 1989; Vosniadou, 1987). In the study presented here, students have multiple experiences with the causal form in one science context but with different problem details. These repeated experiences have been shown to be important to helping students extract the problem schemata by attending to the common causal relations of the situations while disregarding details particular to specific cases (Chen & Deahler, 1989; Gholson, Eymard, Morgan, & Kamhi, 1987; Gick & Holyoak, 1983; Holyoak, 1984). Analogical reasoning can also

lead to new misconceptions if students over-extend the analogy, however, presenting multiple cases tends to help address this problem (Spiro, Feltovich, Coulson, & Anderson, 1989).

Following from Gentner's structure mapping theory (Gentner, 1983), the assumption here is that as students engage in repeated examples of the particular causality in question, their causal analogical reasoning would become increasingly generative. That is to say, they would become more adept at conjecturing the possibility that an analogical causal relationship exists and then would map from their collection of sources to the target concepts, rejecting those that do not fit and enriching their understanding of the causal form for those that do. While analogical reasoning is typically construed to enable understanding from the base problem to the transfer problem, there is evidence to suggest that even when the base problem is not that well understood, the relational comparison of the two concepts enables deeper insight into each (Kurtz, Miao, & Gentner, 2001; Wong, 1993).

While even isomorphic transfer is not common without support (e.g. Brown, 1989; Holyoak, Junn & Billman, 1984) and typically students need help noticing the analogy, we had seen some evidence of spontaneous transfer in earlier phases of our work. There were instances in interviews when students remarked on the type of causal relationship in a topic for which they had not been directly taught the causal structure. This encouraged a more formal test of the possibility.

What might students learn from first cases of causality that could encourage the second type of transfer—non-isomorphic? One of the challenges of transfer is sensitivity to the opportunity to transfer from a base analogy to a target analogy. We hypothesized that students might become sensitive to the existence of a causal structure that needs to be attended to. Familiarizing students with the underlying causal structure in the context of two science topics might alert students to the need to consider underlying causality and the nature of the particular causality in question. Any attempts to map the causal structure as they did in the earlier units should lead to the discovery of a new causal structure. Again, we recognized that the likelihood of such transfer was low, particularly given findings that suggest sensitivity to be one of the largest hurdles in transfer of modes of thinking (Perkins, Tishman, Donis, Ritchhart, & Andrade, 2000). However, as former educators, we were also pessimistic about the likelihood that the deep structures of causality would be taught across most units given how crowded the curriculum is. Therefore, we wanted to test the possibility of spontaneous transfer once students had been exposed to a few units emphasizing the underlying causal structures.

Bransford and Schwartz (1999) have made a compelling argument that our traditional notions of transfer are too limited. Traditional transfer involves the use of a concept taught in one context in another context. Bransford and Schwartz suggest that it is important to consider not only whether the specific understandings taught transfer to new contexts but whether the intervention impacts students' ability to learn future related concepts or "Preparation for Future Transfer" or (PFL). They offer examples from research (e.g. Burgess & Brophy, n.d. as cited in Bransford & Schwartz, 1999) where students call into play previous learning experiences to help them structure new ones. They argue that transfer is evident when students begin "knowing with" (Broudy, 1977) the information that they have learned. While this does not imply knowing things on demand, in what Bransford and Schwartz refer to as Sequestered Problem-Solving (SPS) typical in most Direct Application (DA) tests of transfer, it means drawing upon our cumulative set of experiences in how we approach any given problem. Further, as pointed out by Broudy (1977), "knowing with" knowledge tends to be tacit so it depends upon the context to elicit it. We hypothesized here that students would learn to think about science concepts differently through exposure to the causal forms. We expected that they would attend to concepts more deeply and realize, tacitly, that there are deep structures that have great importance for the

concepts that they are learning and that these structures can play a role in uniting disparate facts of information into a coherent explanatory structure.

### Difficulties of Understanding on the Particular Science Topics Studied

There is a history of research on each of the topics that were taught, outlining the kinds of misconceptions or alternative that students tend to have. Some of the difficulties appear to stem from general features in students' reasoning. Driver and colleagues (Driver et al., 1985) outlined characteristics of student thinking which they found impede students' ability to grasp scientific concepts. A number of these concern how students reason about causality, for instance, focusing on changes as opposed to steady states and subsequently failing to see a need to explain systems in equilibrium, or, for instance, the tendency to engage in linear causal reasoning by looking only for sequential chains of causes and effects when systemic patterns are in play. Brown (1995) identified core causal intuitions that can lead students astray when learning difficult science concepts. He identifies a number of types of attributions of agency—initiating, initiated, reactive, and so on—that can be misapplied. Andersson (1986) draws upon Lakoff and Johnson's (1980) notion of an experiential gestalt of causation as a possible underlying element in scientific misconceptions. He considers how students extend the primitive notion, learned in infancy, of an agent that physically affects an object to a sense of "the nearer, the greater the effect." Andersson outlines how such primitive notions play a role in difficulties students have in learning various science concepts.

On the other hand, there are some aspects of science concepts that do not appear to have generalizable features to them. diSessa (1993) introduced the concept of phenomenological primitives (p-prims), small knowledge structures that people use to describe a system's behavior. They are elicited by particular contexts and come into play as ready explanations or components of explanations. They are considered to be self-explanatory and to need no justification.

Our expectation was that we would be able to impact student understanding on topics where key difficulties of understanding stemmed from the sorts of patterns outlined by Driver and colleagues (1985) and as demonstrated by our previous research and that these were the understandings that would transfer to new topics. We also recognized that each topic had idiosyncratic characteristics that might elicit particular p-prims and that these were unlikely to be impacted by the intervention or result in transferable knowledge. What were the underlying causal patterns in the particular topics studied that we expected would be transferable? Below, we outline the aspects of causality in each topic that should apply more generally across concepts.

*Density.* Density and the related phenomena of floating and sinking are concepts that pose considerable challenges to learners. Most students hold undifferentiated weight and density conceptions (Smith, Carey & Wisner, 1985; Smith, Maclin, Grosslight, & Davis, 1997; Smith, Snir, & Grosslight, 1992). Smith and colleagues (1985) found that in the case of density, students typically attend to only one feature of an object (weight, size, or shape), with one often having more salience for them than the other and typically attend to only one feature of a kind of material (a liquid is thin, thick, or loose). The salience of the surface features (especially felt weight) attracts students' attention making it unlikely that they will look beyond it to infer the existence of density. Students have a similarly limited focus when reasoning about sinking and floating. Typically, students focus only on the object that they are testing to see if it sinks or floats (Kohn, 1993). In other words, they do not focus relationally when attempting to describe the cause of sinking and floating. Raghavan, Sartoris, and Glaser (1998) found that prior to instruction only two students of 36 revealed some understanding of the significance of relative density. Most of

the students in their study (28 of 36) focused on properties of helium or air to explain why a helium balloon rises.

The causal structure of density involves a non-obvious causal mechanism. Density is an intensive quantity--its existence must be inferred by holding volume or mass constant and assessing the implications for the other variable (Inhelder & Piaget, 1958). This gives students difficulty (e.g. Bliss, 1995; Rowell & Dawson, 1977). Understanding density also involves understanding relational causality as the form of interaction pattern between causes and effects. Students need to reason about the relationship between mass and volume and understand that if the relationship between them changes, the density changes. Similarly, in understanding the role of density in sinking and floating, students need to reason about the relationship between the densities involved. This relational type of causality involves recognizing that an effect is caused by the relationship, often one of balance or imbalance, between elements of a system. Neither element is the cause by itself. Thinking about relational causality requires a departure from linear, unidirectional forms of causality where one entity acts as a causal agent on another affecting an outcome in one direction only--in a domino-like pattern (Grotzer, 1993; Perkins & Grotzer, 2000). A third characteristic of the causal structure of density is that it is dynamic. While many textbooks lead to a static notion of density by underscoring that it is assigned a number measured at standard conditions without making clarifying what "at standard conditions" means, density changes with temperature and pressure. Understanding the relational causality, the non-obviousness of density, and the dynamic nature of density are aspects of understanding that we expected could transfer.

*Pressure.* The difficulties that students have reasoning about pressure parallel many of those that they have reasoning about density. For instance, students have a hard time with the non-obvious nature of pressure (Basca & Grotzer, 2001; Kariotoglou & Psillos, 1993; Shepardson & Moje, 1994). Historically, air pressure itself was not recognized until 1630 when Torricelli discovered that air pressure was the cause for the height to which water could be pumped out of mineshafts (Burke, 1978). Students typically do not think pressure exists when they cannot easily see an effect. deBerg (1995) found that high school students did realize that the pressure of enclosed air in a syringe increases on compression. They can feel an obvious effect in terms of the increased pressure on their hands. However, 70% also thought the enclosed air did not have air pressure acting when not in compression. Students have difficulty shifting their focus from the apparent features of the task to the less obvious air or water involved in the task (Benson, Wittrock, & Baur, 1993; Tytler, 1998). Shepardson and Moje (1994) found that 35% of fifth graders' observations focused on obvious causes rather than the less obvious variable of air pressure when trying to explain an egg being pushed into a bottle. Even post-demonstration/discussion explanations revealed that although 36% of the students mentioned air pressure, 33% of them still stated fire as the cause of the egg entering the bottle.

Students also tend to reason linearly rather than relationally when thinking about pressure. They focus on a single agent such as the air pressure on the outside of a balloon or a vacuum sucking as causal rather than the effect being the result of a relationship of balance or imbalance. For example, Engel Clough and Driver (1985) found that on a syringe task, there was no significant difference between 12, 14, and 16 year-olds in that half (50%) of each age group explained it in terms of pressure actively 'sucking' or 'pulling'. This linear focus missed broader aspects of the system as a whole. Rollnick and Rutherford (1993) found that elementary school teacher trainees focused on the air pressure on the outside of the cup in explaining why an overturned cup of water remained intact with a piece of cardboard under it and never mentioned the air on the inside of the cup in constructing their causal explanations. Likewise, Sere (1982) found that 11-13 year-old French children could not imagine pressure without some type of movement associated with

it. They considered equilibrium situations to be due to a lack of pressure rather than due to equilibrium between pressing forces.

Like density, air pressure is also dynamic. As volume and temperature change (and as taught through Boyles' and Charles' Laws), pressure changes. While students do tend to recognize that pressure changes, they are likely to associate changes with a force conception, that pressure involves movement and that it pushes in a uni-directional fashion. They are less likely to attribute its dynamics to the result of balance or imbalance between areas of pressure.

*Heat and Temperature.* There are a number of causal challenges in understanding heat and temperature. Most diverge from those in density and pressure. At one level of explanation, transfer of thermal energy is caused by an imbalance or a differential. Therefore, the cause of heat transfer is a type of relational causality. At a more zoomed-in level, the agency is distributed and while you have the net effect of thermal equilibrium, individual atoms aren't aiming to cause thermal equilibrium, they are merely moving away from other excited atoms. Students tend not to reason about heat and temperature on the particulate level unless they have had explicit instruction on the kinetic-molecular theory of matter (Driver, 1984). They tend to think of hot and cold as substances (Harris, 1981; Watts & Gilbert, 1985) as opposed to processes (Chi 1992) and not necessarily as part of the same continuum (Engel Clough & Driver, 1985). Although the cause of heat "flow" is at one level relational, the pattern of heat "flow" is always unidirectional. Children tend to think of "hot" and "cold" as entities and that the sensation in their hand created by heat energy moving away is always created by hot or cold moving towards their hands (Engel Clough & Driver, 1985).

Like pressure and density, heating can be difficult to understand because the actual cause(s) are the atoms and those are non-obvious. There are two causal interaction patterns in the three commonly taught types of heat transfer. Conduction is a type of multiple linear domino causality. Faster moving particles bump slower moving ones and energy is transferred until equilibrium is reached. Convection is a cyclic form of causality that results from uneven heating. Warmer matter is less dense and floats on colder, denser matter. As matter is warmed it, becomes less dense which causes it to float on the denser, colder matter, where it typically cools, becoming denser and sinking as warmer matter floats on it. The pattern is driven by the heat source. Radiation is a type of multiple linear domino causality with a radiating pattern.

The study described below involved teaching each of these topics in turn and testing for the possibility of transfer of learning either the particular causal concepts or the tendency to look for and consider causal concepts more generally.

## *Methods*

### Design

Five eighth grade science classes from a suburban school system in the Boston area where the populations range from lower to middle class participated. 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. Units were taught in the same order to each of the classes. Some classes received causal interventions as outlined in Table 1.

Table 1. Transfer: Experimental Groups

|  | Class 1- Control No Intervention (CON) Group  | Class 2- Partial Control- Teaching of Non-isomorphic (#2) Form Only (NFO) Group | Class 3- Partial Control- Teaching of Isomorphic (#1) Form Only (IF) Group | Class 4- Causal Forms (CF) Group                                  | Class 5- Causal Forms with Direct Teaching (CFDT) Group           |
|--|---|---|--|---|---|
| Unit 1 Density (relational causality)          | no causal intervention (Basic Density)        | no causal intervention (Basic Density)  | Teaching of causal form #1: relational causality (Causal Density)          | Teaching of causal form #1: relational causality (Causal Density) | Teaching of causal form #1: relational causality (Causal Density) |
| Unit 2 Pressure (relational causality)         | no causal intervention (Basic Pressure)       | no causal intervention (Basic Pressure)   | no causal intervention (Basic Pressure)                                    | Teaching of form #1: relational causality (Causal Pressure)       | Teaching of form #1: relational causality (Causal Pressure)       |
| Unit 3 Heat and Temperature (cyclic causality) | no causal intervention (Basic H&T)            | Teaching of form #2: cyclic and domino causality (Causal H & T)                 | no causal intervention (Basic H&T)   | no causal intervention (Basic H&T)                                | Teaching of form #2: cyclic and domino causality (Causal H & T)   |
| Unit 4   | no causal intervention/ teacher designed unit | no causal intervention/ teacher designed unit                                   | no causal intervention/ teacher designed unit                              | no causal intervention/ teacher designed unit                     | no causal intervention/ teacher designed unit                     |

Students in the intervention classes were engaged in exploring and learning about the nature of the causal forms present in the curriculum concepts for the topic of density (relational causality as in density differentials that contribute to sinking and floating). The scientifically accepted model with the embedded causal structure was put forth 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. Next, students learned a new topic—pressure—with isomorphic embedded cause and effect (relational causality as in pressure differentials that contribute to weather patterns). This enabled an assessment of the first level of transfer. Then students learned a third topic with a number of forms of non-isomorphic embedded cause and effect (for instance, domino causality in conduction and cyclic causality in convection). This enabled an assessment of the second level of transfer. Finally, students were taught a fourth unit without assistance from the researchers (geological processes), comparing it to the control class, to consider the third level of transfer—whether opportunities to learn about causality appear to impact their ability to learn about science concepts more generally. The causal units included activities designed to REveal the underlying CAusal STructure or RECAST activities (described above) and discussion about the nature of causality.

Students took a pre-inventory prior to each unit and a post-inventory following each unit. The same three students from each class (n = 18) (balanced groups chosen by the teachers to represent high, medium, and low achievers) were interviewed following each unit. Relevant work samples were collected throughout the units and classroom discussion was videotaped for later analysis.

## Tasks

### *Assessments*

The assessments were group-administered paper and pencil tasks and individually-administered interview items 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) that were based upon instruments by Smith, Carey, and Wisner (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 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 and to explain each. 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, and 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. 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 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 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.

*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 density 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. 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 some of the 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 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. For instance, "Does what we learned about relational causality help you to think about any of the questions here?"

*Heat and Temperature Assessments.* The heat and temperature inventory consisted of three sections each with three parts for a total of nine questions. The questions were open-ended and students were asked to draw and explain models of the heating processes in each of three situations involving conduction, convection, and radiation. Two of the questions drew upon understanding of more than one heating process and related concepts. For instance, students were asked to analyze what happens when a heater is turned on in one part of a room (so that there is uneven heating) when it is very cold outside. Students discussed the situation primarily in terms of convection, but also included radiation in their response. The questions probed whether students held a substance or process-like notion of heating (Chi, 1992), whether they understood that thermal energy is uni-directional and moves from hotter to colder, that transfer of thermal energy is caused by an imbalance or differential (thus a relational causality is involved); that conduction follows a domino-like causality, and that convection follows a cyclic causality. The assessment was developed for the current research study and was tested with a group of approximately 175 students who were not participating in the formal research.

The heat and temperature interview had four sections, the first three focused on each of the sections in the inventory and a final section that focused specifically on the transfer of causality. As with the other interviews, 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 until if they didn't spontaneously mention it, they were asked a direct question. For instance, "Does what we learned about causality help you to think about any of the questions here?"

*Follow-up Assessment.* The follow-up assessment consisted of four sections. Each section probed understanding of one of the topics that had been learned during the course of the year, density, pressure, heat and temperature, and in addition, geology and the rock cycle, the final topic taught during the year. The questions were designed to assess the persistence of earlier understandings and to consider students' preparation for future learning (PFL) in terms of how their ability to learn about the fourth topic, geology, differed by group.

### *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 also involves 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 a Basic Pressure unit and others in a Causal Pressure unit 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. A computer simulation, Stark Design Molecular Dynamics (Stark Design, 1999), 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. Concrete examples have been shown to enhance transfer because they allow students to discover the relevance of the target concept (Bransford, Vye, Kinzer, & Risko, 1990). 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.

*Heat and Temperature.* Again some classes participated in a Basic Heat unit and Temperature and others in a Causal Heat and Temperature unit according to the experimental design as outlined in Table 1. Each unit had 12 lessons and was divided into three sections. The first section focused on changes of state and how it relates to the adding or removal of energy. The second section focused on the differences between heat and temperature and the concept of thermal equilibrium. The third section introduced the transfer of thermal energy and specifically, conduction, convection, and radiation. Both units included measuring change in temperature during phase change using PASCO probes and analyzing the resulting patterns, learning about evaporation and boiling as cooling processes, seeing that liquids at the same temperature do not

have the same ability to heat (specific heat), learning to think about temperature in terms of kinetic energy, holding an ice cube and learning that energy movement is from warmer to cooler, doing experiments to learn about thermal equilibrium, and doing experiments and watching demonstrations of conduction, convection, and radiation. The heat and temperature units differed from the other units in that all of the activities in the basic and causal version were identical, only the discussion differed in that the causal version explicitly discussed causality. The causal version introduced domino and cyclic causality and included discussion of the difficulties of thinking about heat transfer as uni-directional from warmer to cooler when one notices effects in both directions (for instance, when they hold an ice cube in their hands and the ice cube melts and their hand becomes numb.)

*Geological Processes.* The final unit was not selected for the causal concepts it presented. Rather it was chosen by the teachers and investigated as an instance of “Preparation for Future Learning.” All students participated in the same unit and no causal concepts were introduced.

### Scoring

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. (An example of a rubric from pressure is included in the appendix.) 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

For each topic, data was scored by two independent scorers and inter-rater reliability was assessed. The first round of scoring involved discussing categories of difficulty in scoring (without discussing individual cases) and typically resulted in modifications or clarifications to the scoring system. Then a second round of scoring was used to check that the scoring system was being applied reliably. Finally remaining cases were discussed until 100% agreement was reached.

Table 2. Inter-rater Reliability Scores Across Total Inventory Questions:

|                 | Density                | Pressure               | Heat and Temperature   | Geological Processes   |
|-----------------|------------------------|------------------------|------------------------|------------------------|
| First Round     | $\underline{r} = .85$  | $\underline{r} = .91$  | $\underline{r} = .84$  | $\underline{r} = .88$  |
| Second Round    | $\underline{r} = .91$  | $\underline{r} = .95$  | $\underline{r} = .91$  | $\underline{r} = .95$  |
| With Discussion | $\underline{r} = 1.00$ | $\underline{r} = 1.00$ | $\underline{r} = 1.00$ | $\underline{r} = 1.00$ |

## Results

This phase (Year One) of the data collection and analysis addresses the question of whether transfer occurs with no explicit support. The analysis compared the performance of five classes each receiving a different form of intervention: 1) students in a direct teaching of causal forms condition (CFDT) who were directly taught the causal forms in each unit; 2) students in an isomorphic forms transfer group (IFT) who were taught the causal forms in the first unit but were NOT taught the causal forms in a second unit with isomorphic causality (or in subsequent units with non-isomorphic forms) to test transfer to units that had the same causal structure; 3) students in a direct teaching of isomorphic causal forms group but not non-isomorphic forms (CFI) who were directly taught the causal forms in the first two units but not the third to test transfer to units with a different causal structure; 4) students in a direct teaching of only the non-isomorphic form (NFO) who were taught the causal form in the third unit only to compare to those who had teaching of the causal forms in all three units and; 5) control students who did not have any opportunities to learn relational causal forms (CON). There were no significant starting differences on initial scores based on a Tukey-Kramer HSD comparison and intervention condition explained little of the variance between groups ( $R^2 = .06$ ). The measures used were researcher -designed inventories that were piloted in an earlier phase of the research.

The analysis first looked at post-test performance on the first topic (density). Students across groups showed significant pre- to post-test gains ( $t(130) = -12.05, p < .0001$ ) with a fair amount of variance in student performance (pretest:  $M = 25.62, SD = 9.31$ ; post-test:  $M = 35.07, SD = 9.36$ ). Intervention condition and density pre-test score (initial scores) were plotted against density post-test scores in a multiple regression model ( $R^2 = .41$ ). It revealed significant main effects of intervention condition ( $F(1, 128) = 27.24, p < .0001$ ) and pretest performance ( $F(1, 128) = 44.98, p < .0001$ ). Students with direct teaching of causal forms outperformed those without ( $t(133) = -5.22, p < .0001$ ) with least squares means of 38.48 ( $SE = .90$ ) and 31.85 ( $SE = .87$ ), respectively.

The analysis next looked at whether these gains would transfer to understanding of a second topic (pressure). The pretest for the second unit showed a significant difference by intervention condition and the variance explained by intervention condition went up slightly as compared to the first unit pretest ( $R^2 = .15$ ) with those students who learned the causal forms in the previous unit ( $M = 17.91, SD = 5.39$ ) outperforming those who did not ( $M = 13.76, SD = 4.73$ ). There were significant main effects of intervention condition on the pretest ( $t(117) = -4.47, p < .0001$ ). This suggests that a small portion of the variance on the pretest may be explained by intervention condition and therefore there may be some very small transfer effects present on the pretest. Students across groups showed significant pre- to post-test gains ( $t(110) = -16.46, p < .0001$ ) with a fair amount of variance in student performance (pretest:  $M = 15.78, SD = 5.46$ ; post-test:  $M = 22.97, SD = 5.77$ ). Intervention condition and initial scores were then plotted against pressure post-test scores in a multiple regression model ( $R^2 = .23$ ). The effect test shows significant main effects of intervention condition ( $F(2, 123) = 5.23, p = .0066$ ) and initial performance ( $F(1, 123) = 16.76, p < .0001$ ). Interestingly, the group with direct teaching only on the first topic (IFT) outperformed the group with direct teaching in both topics and that group outperformed the controls with least squares means of 25.45 ( $SE = 1.14$ ), 23.96 ( $SE = .79$ ), and 21.56 ( $SE = .66$ ). Initial scores were used in the model rather than pressure pretest scores because it appears that pressure pretest scores are impacted differentially by intervention condition and therefore explain portions of the same variance as intervention condition. The data suggests that there is some modest transfer from one topic to another when the embedded causal patterns are the same.

Figure 1.  
Prediction Formula Detailing Parameter Estimates (Intervention Condition and Inventory Version) to Estimate Pressure Post-test Scores

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$$\text{Intercept} = 18.20 + \left\{ \begin{array}{l} \text{match} \\ -2.10 \\ 1.80 \\ 0.30 \end{array} \right. \begin{array}{l} \textit{Intervention} \\ \textit{Condition} \\ \text{when Control} \\ \text{when IFT} \\ \text{when CFDT} \end{array} \left. \right\} + 0.21 \times \text{initial score (Density pretest)}$$


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Next, we tested for transfer to a third topic, heat and temperature, where the causal forms were non-isomorphic to those in the first two topics. There were no significant pre-test differences between the groups suggesting that there was no spontaneous transfer due to the causal interventions. Students across groups showed significant pre- to post-test gains ( $t(124) = -12.65$ ,  $p < .0001$ ) with a fair amount of variance in student performance (pretest:  $M = 8.87$ ,  $SD = 4.91$ ; post-test:  $M = 14.92$ ,  $SD = 5.50$ ). No significant differences between groups were found. This suggests that non-supported, non-isomorphic transfer did not occur.

Finally, we tested for transfer to a fourth topic, geological processes, with no direct teaching of causality to any groups to see if the students were better prepared for learning in the sense that they might attend to the causality involved. In support of our hypothesis but to our actual surprise, there was a significant main effect of intervention condition ( $F(2, 132) = 0.41$ ,  $p < .0001$ ) and the model explains a small amount of the variance ( $R^2 = .19$ ). All of the groups that had causal teaching in at least one of the first three units except the group that only experienced direct causal teaching on the third topic significantly outperformed the control students as determined by a Tukey-Kramer HSD Test (CFI, CFDT, IFT > CON, (Abs(Dif) - LSD = 0.53, 0.31, 0.14, respectively,  $p < .05$ ). In addition, the group with direct teaching of causality on the first two units only significantly outperformed the group that had causal teaching on the third unit only (CFI > NF, (Abs(Dif) - LSD = 0.02,  $p < .05$ ). This suggests that there may have been minimal effects of the causal intervention on learning more generally. Our surprise stemmed from the lack of differences found on the third unit and the fact that some of the causal forms inherent in the fourth topic, geological processes, were more similar to that of the third topic, heat and temperature, than to others. It suggests that there may be reasons to examine the heat and temperature unit and how effective it was aside from questions of transfer. It also suggests that some more general learning may have occurred although we consider this finding highly tentative at this point.

The students' interviews offer a sense of the qualitative differences of what student attempts to map the analogical relationships looked like. It was typically in student interviews for them to begin to realize the isomorphic causality between density and pressure even if they had not done so earlier. Sita participated in the group that had exposure to relational causality in the density unit but not in the pressure unit (IF). In the excerpt below, we hear Sita reasoning through the relationships once the sensitivity issue has been removed by the researcher asking her whether relational causality applies to anything in the pressure unit. Most of Sita's answers on the post-test are relational in form although she does not seem to have an explicit awareness of it. For instance on question one:

Interviewer: "Why does the balloon deflate when you bring it from the mountaintop to the beach?"

Sita: "The pressure is lower up on top of the mountain because there are less layers of atmosphere there. ...[at the beach] there was a lot more pressure pushing on it. The pressure of that the air inside the balloon was exerting was not as much that was pushing on the balloon so it got partially deflated. ...When she brought it down, there is a lot more layers of atmosphere on it, so that means there is a lot more pressure pushing down onto the balloon than there was up here (pointing to top of mountain). But the balloon is exerting the same amount, and there's more pushing in, so it makes it deflate a little more."

On question three, "Why are people advised to open windows in a hurricane?" she reverses where high and low pressure are located (a common misconception because students think of the powerful force of a hurricane as having to do with high pressure) but clearly reasons relationally:

Sita: "When a hurricane happens, there's a lot of high pressure in that area. And the air inside your house is exerting the same amount of pressure that it always was. ...in a regular hurricane, it won't damage your house, but in a really strong hurricane, then all the pressure on all sides of the house are pushing and it'll, like, cause it to collapse because there is more pressure pushing onto the house than there is pushing inside of the house. If you open your windows, then the high pressure can come in. Then the pressures will become equal and no explosion or crushing can occur."

At the same time, she realizes that "Wind is just the movement of high pressure to low pressure." She also mentions the non-obviousness of pressure.

Sita: "I think we only notice it [pressure] when there is a difference in it. Cause right now we don't feel all the pressure pushing down on us--but because we exert the same amount, we don't feel it. But when we go up in a plane, the difference in air pressure causes our ears to pop."

However, when explicitly asked to consider whether any of the phenomena have to do with relational causality, she reveals an "aha" experience. Transferring the understandings in an explicit way engage the students in two challenges. The first is sensitivity to the possibility that the relationship might transfer. This was addressed by our direct cueing in the interview. The second is the actual mapping of the relationship components. Here we hear Sita struggling with this part as well. In some cases she talked it through and was in the end able to map it on her own. In other cases, as illustrated below, she focused on other relationships and did not see the target for the relational one. When asked to go back to the questions with relational causality in mind, she had the following to say about the straw question [Explain what happens when you drink from a straw].

Sita: "Wait yeah, actually, in a way, it is because this liquid going up happens because there is a lower pressure here. 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 it like in a way it is relation. ...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."

On the hurricane question, she had this to say,

Sita: "I kinda think they are two independent things. There's pressure exerting and there's pressure pushing on the house. All you're doing is opening windows so the house doesn't collapse. Nothing is based on something else as far as I can see." When asked, "What are the two independent things in this case?" she said, "The pressure pushing on the house, that's got nothing to do with the inside pressure. And the pressure inside the house, is just what is what is supposed to be at sea level. But there's a change in the atmosphere, which is causing the outside pressure to change. So yeah, yeah, wait!! There IS a relational cause for the pressure outside. Because of the hurricane, it is causing the pressure to change, but the inside pressure is staying the same, nothing is happening to the inside pressure. But when you're opening the window, you're trying to get everything to be equal so that you're back at normal."

Interviewer: "Where's the relational piece there?"

Sita: "The outside pressure. How the outside pressure is changing."

Interviewer: "What is it in relation to?"

Sita: "To the regular pressure. Let's say the pressure outside and inside a house was always what it is when a hurricane happens, then nothing would happen. But because pressure is not like that, it's lower than that, then because the hurricane happens, it is causing the outside air pressure to change. But the pressure inside, nothing happens, because it's not acting on the inside of the house. There's low pressure here, the regular air pressure, and the hurricane pressure, its (hurricane pressure) stronger, and it exerts more pressure than the air pressure so it comes in and pushes it away and takes the place of the regular air pressure. That's why you open the windows..."

Sita's responses suggest that she has incorporated the relational causal model into her reasoning as tacit knowledge. She even applies it appropriately in some instances. She just wasn't explicitly aware that she was doing so until the interviewer cued her to be sensitive to it.

### *Discussion*

These results give a mixed picture for the unsupported transfer of causal forms but suggest that transfer is indeed possible. Broadly, it suggests that in the case of isomorphic forms, students can adopt the causal forms and transfer them to some extent even if, as in the example above, they may do so tacitly. Unsupported non-isomorphic transfer appears to be unlikely. Transfer in terms of "Preparation for Future Learning" also looks promising but given the contradictions in the data, further research is needed to shed light on this possibility.

A more metacognitive approach to the causal forms may be needed. Perkins (1989) makes a distinction between two types of transfer, "low-road" and "high-road transfer." *Low-road transfer* has an automatic, reflexive quality. Routines that are well-practiced are automatically triggered in situations where there is a great deal of similarity between the two contexts. Examples of this type of transfer are using video game skills learned in one game in a new game or using reading skills in science. *High-road transfer* requires reflective thinking and direct attempts to make connections. The student learns something, abstracts the principles from it, and then applies it elsewhere (forward-reaching) or searches in memory for matches (backward-

reaching). Deeper analogies are sought ? looking past surface similarities, for instance, noticing that different systems of measurement each have a feature called a standard of measure and that these serve a similar purpose despite surface differences in the systems. People are not particularly good at noticing analogies (Gick & Holyoak, 1980, 1983). They need help finding them as well as seeing how some are better than others (Brown, 1989).

Many researchers (e.g. Blank, 1999; Georghiades, 2000; Hogan, 1999; Tishman, Perkins, & Jay, 1995) have argued for the importance of mental management, or metacognition, as a means to support the restructuring of ideas in science or, in other terms, the facilitation of conceptual change. White and Frederiksen (1995) found that metacognitive reflection helped all students and that the lowest performing students experienced the greatest gains. Adey and Shayer (1993) taught the patterns of thinking in science, such as the isolation and control of variables. Students focused on examining their assumptions, metacognition, and transferring of knowledge and strategies between contexts. Performance for many students on math, science, and English achievement tests significantly improved and persisted when measured again two years later.<sup>1</sup> Schoenfeld (1979, 1982, 1989) successfully taught heuristics for mathematical problem-solving. Students performed significantly better. When explicitly taught to self-monitor their thinking, students approached problems more systematically and thoughtfully. They were more likely to sort mathematical problems according to the deep structure (as experts do) than based on surface similarities (as novices do) than other students. These results indicate that metacognition may help improve the transfer of causal structures when learning ideas in science. The type of metacognition also appears to matter. Some researchers have found that students are most able to engage in analogical reasoning and to transfer concepts when they accept the solution as a plausible solution to the target problem (Pauen & Wilkening, 1997) or when they generate the analogies (Pittman, 1999) thus forcing them to seek out the similarity relations (Wong, 1993).

Supported transfer contexts might also involve acquainting students with a greater understanding of various causal forms and relating them to other types of content—such as social instances. Our current research involves supporting transfer by broadening students' awareness of the nature of causality, using everyday examples, incorporating greater metacognition, and involving students in increased connection-making. It also considers what happens when students are given transfer support in either materials-based or teacher-guided contexts.

On balance, this research addresses the causal aspects of understanding that may transfer, however, they don't represent the entire puzzle of transfer of knowledge. All of these topics also involve situation-specific default concepts such as p-prims (diSessa, 1993) that affect transfer. For instance, we have seen students struggle with applying a relational model to situations involving air pressure when they have a strong competing force notion as in explanations of the wind or hurricanes. So while they can apply it in some instances, in others, they oscillate between linear, unidirectional force models and relational explanations. This suggests that teaching of causal forms should be complemented with teaching strategies for helping students address the applicable p-prims within the specific subject matter.

So at this point, the evidence points to some promise but also some humility about the endeavor. With the right kinds of shepherding, it seems that transfer of causal forms can be achieved. The important issue then will be, whether this is shepherding that is likely to work in the culture of schools. The question is worth pursuing because the potential payoff is great. If transfer of causal structures between science concepts can be achieved, it suggests a means to systematically improving students' science learning and therefore would be a high leverage curriculum component and teaching strategy for teachers to include in their practice.

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## Appendix: Lesson Descriptions for Density Unit:

### **Lesson 1: What are volume, mass, and weight? How do we distinguish each one?**

Students learned to distinguish the concepts of volume, mass, and weight. They explored why it was difficult to distinguish between these concepts. Computer simulations allowed them to explore the differences between mass and weight on different planets.

### **Lesson 2: How can we measure mass and weight?**

Students learned how and why mass is measured with a spring scale. Mass is a measurement independent of gravity, it always involves a comparison. Students learned that they find the mass of an object by finding out how many grams it takes to balance the object on a pan balance.

### **Lesson 3: How can we measure volume?**

Students deduced how to measure the volume of regular and irregular objects and practiced measuring them. They learned how to use the displacement method in the case that the object sinks or floats.

### **Lesson 4: Why do some objects of the same volume differ in mass?**

Students considered the problem of how objects made of different materials that have the same volume can have different masses. They compared different objects with the same shape and volume with different masses and drew models of what they thought might be going on.

### **Lesson 5: How do we calculate density?**

Students graphed out the relationship between mass and volume of different objects to find out that density can be deduced by knowing the relationship between mass and volume. They learned that density is measured in units;  $\text{g/cm}^3$  [grams per cubic centimeter] or  $\text{g/ml}$  [grams per milliliter] and that of density, mass, and volume, if you know two of the variables, you can figure out the others.

### **Lesson 6: How do we calculate density?: A reinforcement lesson**

Students used a computer simulation called Archimedes Laboratory to learn how calculations of density relate to visual models. They also discussed the statement in their book, “The density of a liquid can be measured...” and whether the word “measured” is a good or bad choice. They debated whether density be directly measured or has to be inferred.

### **Lesson 7: Why do we say density is a property of a particular kind of matter?**

Students engaged in activities to realize that density is not affected by the size or shape of the object. They learned that specific densities are assigned to specific elements and that the density of a substance can be used to help identify that substance.

### **Lesson 8: Do liquids and gases have density just as solids do?**

Students learned that liquids and gases also have density—that all matter has density. They figured out how to calculate the density of liquids and gases. They found the density of water and a number of other liquids.

### **Lesson 9: What are some useful models of what more or less dense might look like?**

Students analyzed a set of different models for visualizing density and generated a number of their own. They learned that one way to think about density that students often find helpful is to think about how crowded or packed a material is. Many models use various forms of crowdedness (or more or less packed in) as a way of conveying density.

**Lesson 10: What causes differences in density?: The role of atomic mass**

Students in the causal intervention learned to think about the micro causes of density as a way to conceptualize it despite its non-obvious nature. They learned that density has multiple contributing causes and that one cause of differences in density is the masses of the atoms (the number of protons, neutrons and electrons that the atoms are made up of). This cause applies equally to all states of matter. Students in the control condition continued to generate, explore and critique different models for helping them to visualize density as begun in the previous lesson.

**Lesson 11: What else causes differences in density?: The crowdedness of atoms and molecules due to structure, states, and conditions**

Students in the causal intervention learned that another contributing cause to density is at the micro-level is the spacing between atoms due to the strength and structure of atomic bonds between the atoms and the spacing between atoms, molecules, and compounds due to states, structure, or conditions: how far apart the atoms, individual molecules, or molecular compounds are spread with other molecules (such as air or water) or vacuum in between due to various states, structure and/or conditions. Students in the control condition engaged in an activity called “The Penny Lab” designed to help students realize that density is one means of figuring out the composition of an object and they considered pennies that had differences in density and what that implied for their composition.

**Lesson 12: What does it mean for density to have multiple contributing causes?**

Students in the causal intervention learned that density has multiple contributing causes. Not every cause is involved in every situation where density is in play and that you can’t compare objects by using just one of the causes alone. You also can’t assume that every cause contributes to every situation. They explored situations where this was so both in science and social content. Students in the control condition completed “The Penny Lab” activity from the previous lesson.

**Lesson 13: Can the density of a solid change?/ How does density change in liquids and gases?**

Students in the causal condition heated a ball and ring to see that density is not static; it can change and analyzed what happened using the micro-causes of density and the relationship between mass and volume. They learned that changing the temperature (and pressure) can change the density of a substance and that solids (and liquids) expand a little when heated. Gases expand a lot when heated. Students in the control condition learned what it means to assign a number to elements that represent “standard density.”

**Lesson 14: How does density affect sinking and floating?**

Students in the causal group did a RECAST activity to help them realize that when considering whether an object will sink or float in a liquid, you have to compare the density of the object to the density of the liquid. They discussed linear and relational causal models and they layered liquids to see the relational density. Students in the control condition learned that an object made of a substance with a density greater than 1.0 will sink in water, an object made of a substance with a density less than 1.0 will float in water, and an object with a density of 1.0 will suspend in water, controlling for other variables.

**Lesson 15: How does density affect sinking and floating?: A reinforcement lesson**

Students in both conditions used Archimedes Laboratory to experiment with sinking and floating. Students in the causal condition had their experimentation guided and supported by a sheet that helped them to interpret what was happening through the lens of relational causality while

students in the control condition used an unmodified version of the program (but also had a written guide sheet for their work).

**Lesson 16: Manipulating variables: What is going on in the relationship of densities to explain sinking or floating?**

Students in the causal condition manipulated the variables in the relationship that determines what sinks or floats to modify the outcomes. Students found that Diet Pepsi floats while regular Pepsi sinks and they discussed why. Then they generated ideas for and modified the liquid it was floating in to make both sink. The exploration and the models students generated to explain it were considered through the lens of relational causality and the dynamic nature of density. Students in the control condition experimented with objects to see which would sink and which would float in water. They then deduced information about the object's density.

**Lesson 17: What happens when you mix densities?**


Students planned and created objects that would suspend by using mixed density. Students in the causal condition analyzed and planned their objects through the lens of relational causality. Students in the control condition analyzed and planned their object to have a density similar to that of water (1 g/ml)

## Appendix: Pressure Inventory Causal Understandings Rubric: General Overview and Sample Criteria for Question One

The cause and effect relationships for the questions on the Unit Inventory have a specific structure to them. This rubric assesses whether students understand the scientifically correct causal structure. A student may have the right causal structure (in this case, a pressure differential) but the wrong scientific information to support it. A second rubric assesses students' grasp of the scientific information. Ultimately, the goal is for the student to have both; the correct causal structure and the correct scientific information AND students cannot have the correct scientific knowledge without having the correct causal model. Separating the causal structure from the scientific information helps in assessing where students' learning difficulties may be.

Typically, students have the following kinds of causal models when reasoning about pressure concepts. You will see each of these represented in the rubrics below.

Least Complex

- 
1. A model that recognizes only obvious causes and therefore, does not recognize the role of air pressure.
  2. A model that uses the term 'pressure' as a token explanation with little elaboration to support it
  3. A model that focuses on one side of the pressure differential only
  4. A pressure differential model in which each side of the relationship is acknowledged, but there is no reference to the interaction between the two sides of the relationship
  5. A pressure differential model in which both sides of the relationship are noted as well as the interaction between them

Most Complex

Rubrics are often designed so that each scale looks at just one component of understanding. However, the non-obviousness of pressure as a variable relates directly to students' ability to detect a relational causal model. For this reason, this rubric collapses the two causal understanding goals: 1) using relational causality and; 2) identifying a non-obvious variable.

What is a token explanation?

A token explanation invokes the idea of pressure (or another causal agent) in a surface way only, attributing any or all effects to this agent without any explanation or elaboration. Some common examples are:

"Pressure made it happen."

"Pressure is working in this system, that's why it happened."

"Pressure caused it to rise."

"The liquid is forced up the straw when you suck because of pressure."

1. Jan buys a thank-you balloon for her house sitter while on vacation in the mountains. After driving home to her beach house on the coast the balloon is partially deflated. Why do you think the balloon deflated?

| Causal Understanding  |   |  |  |  |  |
|---|---|--|--|--|--|
| Least Complex   |   |  | Most Complex   |  |  |
| ←   |   |  | →  |  |  |
| The student...  |   |  |  |  |  |
| 0   | 1   | 2  | 3  | 4  | 5  |
| ...repeats question, gives a non-causal response, or elaborates on background variables | ...attributes cause to obvious variables such as a hole in the balloon or that the air leaked out, <b>or</b> mentions pressure ( <b>or</b> any other non-obvious variable) as a token explanation | ...acknowledges a difference or change in pressure but does not elaborate, <b>or</b> uses non-obvious variables other than pressure, such as temperature | ...focuses on one side of the pressure differential/ equation only | ...mentions both sides of the pressure differential/ equation but does not acknowledge their interaction | ...implicitly or explicitly acknowledges the pressure differential/ equation and interaction |
| Other- Responses that do not fit any of the categories above                            |   |  |  |  |  |

\*\*Note- For the students' illustrations, a student does not need to have both drawings (mountain and beach) to model a relational perspective.

Some obvious variables or descriptions:

Altitude  
Atmosphere

Some non-obvious variables or descriptions:

Gravity  
Thin or thick air  
Helium  
Density  
Temperature

**Prototypical responses:**

These are some of the most common responses for each level. Most are taken or modified from pilot data.

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

"The balloon deflated when she got to the coast."

"It just happened, the balloon just deflated."

"Jan started out in the mountains and drove all the way to the beach, which takes a long time."

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

"There must have been a hole in the balloon, so the air all escaped."

"I think the balloon wasn't tied tightly, so the air leaked out."

"The balloon deflated because of pressure."

"It's hot at the beach, so moving from the cold weather in the mountains to the hot weather at the beach caused the balloon to deflate."

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

"The pressure is different in the mountains than it is at the beach, and that made the balloon deflate."

"I think one possibility that caused the balloon to deflate would be the change of pressure in the surroundings."

Level 3: The student focuses on one side of the pressure differential/equation only

"In the mountains where she bought the balloon there is less pressure. On the coast the air has more pressure so it deflated."

"Because the air pressure is so high in the mountains, when she goes down to the beach where it's less, the balloon deflates." [Scientifically inaccurate]

"When the balloon got filled up in the mountains, the pressure in it was high. So when she drove down to the beach, the pressure inside the balloon got less, and the balloon deflated." [Scientifically inaccurate]

Level 4: The student mentions both sides of the pressure differential/ equation but does not acknowledge their interaction

"The pressure from the mountains to the beach changes, but the pressure in the balloon doesn't change, so the balloon deflated."

Level 5: The student implicitly or explicitly acknowledges the pressure differential/ equation and interaction

"I think the balloon deflated because the pressure changed outside the balloon. The pressure increased, making it harder for the gas inside to expand, then making the balloon deflate a little."

"In the mountains there is less pressure than at the beach. When she bought the balloon in the mountains, there was less pressure on the gas inside, so the balloon can expand all the way. When she drove down to her beach house, the pressure outside on the balloon increased, and the air inside the balloon moved closer together or got more dense, since there is not enough gas inside to make it hold its shape. So it shrank a little."

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