Transferring Structural Knowledge about the Nature of Causality to Isomorphic and Non-Isomorphic Topics

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Overview

Scientifically accepted explanations often require students to structure knowledge in ways that contradict their expectations about the nature of how causes and effects behave. Previous research suggests that experts and novices typically structure their explanations differently, emphasizing different dimensions of complexity (Feltovich, Spiro, & Coulson, 1993), forms of causality (e.g. Chi, 2000; Grotzer, 2004; Perkins & Grotzer, 2000; Resnick, 1996), and different aspects of analysis (e.g. Hmelo-Silver & Pfeffer, 2004).

Helping students to reflect upon and revise their assumptions about the nature of causality in the context of their science learning has been effective in helping them restructure their knowledge and achieve scientific understandings (e.g. Perkins & Grotzer, 2000; Grotzer 2002). Across topics (electricity, ecosystems, density, air pressure) and across ages (third through 11th grade), students who were exposed to activities and discussion designed to reveal the underlying causality of the topic outperformed students who participated in the same units minus those features (e.g. Grotzer, 2000; Grotzer & Basca, 2003; Perkins & Grotzer, in press).

However, transfer of learning is one of the abiding challenges of pedagogy (e.g. Bransford & Schwartz, 1999; Detterman & Sternberg, 1992; Salomon & Perkins, 1989). Even if students grasp the causal structures and demonstrate deeper understanding of the scientific concepts as taught, can students transfer their causal 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 two studies, each investigating 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) under different conditions of learning.

Introduction

Structural knowledge (e.g., Grotzer, 2002; Jonassen, Beissner, & Yacci, 1993) refers to the fundamental assumptions students make about the nature of knowledge--what counts as a cause and effect relationship, what things can be categorized together, what is countable, and so forth. Scientists often make different assumptions than novices (e.g., Ferrari & Chi, 1998; Hmelo-Silver, Pfeffer, & Malhotra, 2003) and it has been argued that facilitating structural knowledge is as important an educational focus as is facilitating procedural and conceptual knowledge (Grotzer, 2002).

A growing body of research suggests that students hold limiting assumptions about the nature of causality (e.g. Chi, 2000; Driver, Guesne, & Tiberghien, 1985; Grotzer & Bell, 1999; Perkins & Grotzer, 2000; Wilensky & Resnick, 1999) that impact both their understanding of complexity and everyday science (Grotzer, 2004). Feltovich, Spiro and Coulson (1993) described "reductive biases" that pull towards simplification and away from complexity, for instance, reducing dynamic phenomena to static snapshots or breaking continuity into discrete steps. Similar reductive biases have been identified specifically in terms of causal complexity. Grotzer and colleagues (2004; Grotzer & Bell, 1999) identified a set of nine simplifying assumptions that lead to simple notions of causality.[1]

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[1] There are some areas of overlap between the simplifying assumptions identified by Feltovich and colleagues (1993) and by Grotzer (2004). For instance, both identify sequentiality vs. simultaneity, linearity vs. non-linearity, and surface vs. deep level as tensions where people's assumptions tend towards

Table 1. Nine Default Assumptions About the Nature of Causality
That Impede Science Learning

Students assume that causality is:	Example	Instead of:	Example
Linear	When I suck on the straw, I make the juice come up.	Nonlinear	There is less air pressure inside the straw than outside, so the imbalance results in the juice getting pushed up the straw.
Direct without intervening steps	Green plants matter to animals that eat them but not to animals that eat the ones that eat green plants.	Indirect	If the green plants disappeared, it would eventually affect everything in the food web.
Unidirectional	Mice matter to owls because they make food for them, but the owls do not matter to mice.	Bi-directional or mutual	The owls maintain balance in the mice population.
Sequential with step-by-step processes	The electrons crowd onto the circuit and go to each bulb so the first one gets the most power.	Simultaneous	The electrons move like a bicycle chain turning in a circle all at once making the bulb light when it moves.
Constructed from obvious, perceptible characteristics	The object sinks because of its weight.	Constructed from non-obvious or imperceptible variables	Density affects sinking and floating.
Due to active or intentional agents	The electrons move to make static electricity.	Due to passive or unintentional ones	Protons and electrons are attracted to each other. Bridges stand because of balanced forces. Seat belts passively cause us to stop when the car stops.
Deterministic--effects always follow "causes" or the causal relationship is questioned	I did it before and I didn't get sick, so I'm not going to get sick now.	Probabilistic	Getting sick depends upon many things. Even if I didn't get sick before, I can still get sick now.
Spatially and temporally close to its effects	I can't see any bad effects of getting a suntan right now.	Distant or having delays	The hurtful effects of getting a suntan accumulate and show up after along delay between cause and effect.
Centralized with few agents	The queen bee directs the activity in a beehive.	Decentralized with distributed agency and emergent effects	The interactions of many bees result in an organized system.

For instance, 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). They expect causality to be centralized rather than distributed and deterministic rather than probabilistic (Resnick, 1994; 1996) or emergent (Chi, 2000).

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the first, simpler case. The other dimensions identified by Feltovich et al (1993) and Grotzer (2004) address different aspects of difficulty.

These assumptions are often in opposition to the forms of causality inherent in the subject matter, making it difficult for students to grasp the science involved. For example, students often give linear or narrative explanations that are story-like: First this happened, then it made that happen, and so on. These explanations have a domino-like quality to them. However, most of what students need to learn in science doesn't unfold in a domino-like pattern. Such concepts as symbiosis, pressure or density differentials, and electrical circuits are distinctly nonlinear in form. They involve mutual, relational, or cyclic patterns. Concepts may appear straightforward at first glance, but their complexity becomes clear as soon as one dives below the surface. In addition to nonlinear patterns, they may include nonobvious causes; time delays and spatial gaps between causes and effects; distributed, unintentional agency; and probabilistic causation where the level of correspondence between causes and effects varies.

Impacting Students' Repertoire of Causal Models:

Without opportunities to learn the necessary expert structural knowledge 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. Chi, 2000; Grotzer, 2000; Slotta & Chi, 1999; Wilensky & Resnick, 1999).

A growing body of research supports the importance of offering students opportunities to learn how experts structure knowledge (e.g. Grotzer, 1989, 1993, 2000; Perkins & Grotzer, 2000, in press; Wilensky, 1998). For instance, Chiu, Chou and Liu (2002) found that Cognitive Apprenticeship hade a significant difference in students' ability to grasp concepts of simultaneity and randomness as they relate to understanding chemical equilibrium in contrast to students in a control group. Wilensky and Resnick and colleagues (Resnick, 1996; Wilensky, 1998; Wilensky & Resnick, 1999) have demonstrated that constructionist opportunities to work with dynamic, object-based models that reveal complex causal concepts result in new insights into the nature of complex phenomena such as the gas laws, ecology concepts and behavior of slime molds.

Our earlier research (See e.g. Grotzer & Basca, 2003; Grotzer, 2000; Perkins & Grotzer, 2000, in press) sought to identify and impact the ways that students structured the underlying causality in science concepts. We aimed to broaden students' repertoire of causal models so that they had more sophisticated knowledge about how causes and effects behave. In order to test whether making students aware of their causal assumptions and introducing them to more sophisticated forms impacts their learning of a number of science concepts (electricity, ecosystems, air pressure, and density), we contrasted three treatment conditions as follows:

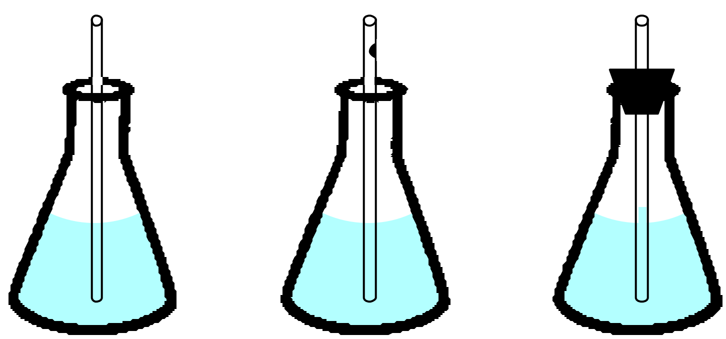
1) Causal Activities and Discussion Group (CAD), in which students participated in activities designed to reveal the underlying causality and in discussion about the nature of causality;
2) Causal Activities Only Group (CAO) in which students participated in the activities designed to reveal the underlying causality but not in the discussion about the nature of causality
3) Control Group (CON) in which where students did not participate in the causally-focused activities or discussion.

In all three conditions, the students participated in "best practices" science units that included extensive model building by students, evaluating evidence, Socratic discussion, dynamic computer models, and attention to students' evolving models. All of the students engaged in modeling their ideas (on white boards, in journals, etc.), sharing and discussing those models, and critiquing the models in terms of which had the most explanatory power given the evidence that students were discovering. The teachers and researchers scaffolded these discussions to help students focus on bringing evidence and counter-evidence to bear on the process of critiquing the models. Students in the intervention conditions engaged in activities designed to reveal the underlying causal structure of a topic and/or discussion about the nature of causality--the specific causal rules and patterns in play--in the context of learning particular science topics. The causal models that were introduced were subject to the same modeling, discussion, and critique for explanatory power as other ideas and simpler models that were put forth by students.

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 variables 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. The outcome encourages students to attend to what is outside the balloon rather than just the balloon itself and to consider the pressure differentials in play--a relational causality. Another activity attempts to help students to reason about the relational causality involved in drinking from a straw. Typically, students they use 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 challenged to see who can drink the liquid the fastest. Two of the flask/straw systems have 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.

Figure 1.

Illustration of Straw-Flask RECAST Activity



1. Flask with Straw — 2. Modification with Hole in Straw — 3. Modification with Stopper in Flask

Across topics, students who had opportunities to grapple with the underlying causal structures and to learn the forms of causality present in the scientifically accepted revealed significantly deeper understanding of concepts that students typically have difficulty grasping (e.g. Grotzer, 2000; Grotzer & Basca, 2003; Perkins & Grotzer, in press). In some topics, electrical circuits, for example, the effect sizes were more dramatic than others, such as density. It appears that the more difficult or counterintuitive the pattern of causality involved, the less likely that students will be able to glean it on their own from instruction that does not in any sense illuminate 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 difficulties in understanding.

Transferring Causal Understandings

The question of transfer is a critical one in gauging the promise of pedagogical innovations. While it is possible to teach the relevant causal forms in the context of each new science concept, it substantially strengthens the argument for teaching about the nature of causality if students are able to transfer their causal knowledge to new contexts. This is especially so given that it is unlikely that all teachers would teach the causal underpinnings of a topic and beyond this, if the causal forms are to have power beyond the world of school, transfer and applicability are critical.

The research reported below investigates the question of transfer with different levels of scaffolding. The first 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). 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). However, given that transfer support is unlikely in the actual world of schools, we decided that it was important to assess an unsupported condition. Further, there was some qualitative evidence of spontaneous transfer in the earlier phases of the research. For instance, students remarked on the type of causal relationship in topics for which they had not been directly taught the causal structure. This encouraged a more formal test of the possibility. The second study asked, "How well does learning about causal structures in one topic transfer to other topics with specific supports (as outlined below) for transfer?"

In both studies, 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 understand and/or to learn about that specific form of causality in another context (in the service of deeper learning of the new science concept?"), hence, isomorphic transfer; 2) traditional "far" transfer which translates here as, "Does learning about specific forms of causality in one context make it easier for students to understand and/or learn other forms of causality (in the service of deeper learning of the science concepts?)" hence, non-isomorphic transfer; 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—considers 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 below, 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), we assumed that as students engaged in repeated examples of particular causal forms, their causal analogical reasoning would become increasing 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).

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. It is possible 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. 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).

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 questioned whether students might learn to think about science concepts differently through exposure to the causal forms. We expected that they might 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 facets of information into a coherent explanatory structure.

Difficulties of Understanding the Particular Science Topics Studied

A history of research on each of the topics that were taught, outlines the kinds of misconceptions or alternative conceptions that students tend to have. Some of the difficulties stem from general features in students' reasoning. Driver and colleagues (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 relating to 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 in the middle school curriculum of focus in both studies 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 & Wiser, 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 that 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, Squires, Rushworth, & Wood-Robinson, 1994). 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 studies 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.

Study #1:

The first study was designed to assess whether or not students would transfer what they had learned about causal forms from one topic to another without explicit support for doing so. It considered the following questions in unsupported contexts:

1. Does learning about specific causal patterns transfer from one topic to another when the embedded causal patterns are isomorphic?
2. Does learning about specific causal forms transfer from one topic to another when the embedded causal forms are non-isomorphic?
3. Does learning about specific causal forms enhance students' ability to learn science more generally--in terms of "Preparation for Future Learning" (Bransford & Schwartz, 1999)?
4. Are the gains that the students make in deeply understanding the science concepts persistent? Do they retain those gains by the end of the school year?

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 2.

Table 2. Transfer Study #1: Experimental Comparisons

	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 Geologic Processes	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). In the intervention and control classes, 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.

<u>Tasks</u>

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, Record, Bell & Grotzer, 2000) that were based upon instruments by Smith, Carey, and Wiser (1985), and others.

Density Assessments. The density inventory consisted of ten questions. Six questions were open-ended and asked students to draw a model and explain the model for each question. Each question targeted a specific type of difficulty that students have in reasoning about density 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 prior to the current study, tested with approximately 186 students, and refined over the subsequent four years. Some questions were from an earlier inventory developed by Smith and colleagues (Smith, Grosslight, Davis, Maclin, Unger, Snir, & Raz, 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 previous to the current study, 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, was tested with a group of approximately 175 students who were not participating in the formal research, and refined based upon their participation.

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, geological processes, 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 added 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 it's 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. Extended descriptions of the units and how the lessons for causal and control students varied can be found in Appendix A.

Density. Control classes participated in Basic Density and Intervention classes participated in Causal Density. Each unit consisted of 17 lessons. 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. Students were taught how patterns of heating and cooling affect global wind patterns; that the total energy received by the Earth is balanced by the total energy emitted from the planet (conservation of energy); the concept of geologic time (as compared to historical time); and about the structure of the Earth and plate tectonics. They also were introduced to the rock cycle and different categories of rock (Igneous, Sedimentary, and Metamorphic) and different minerals as the 'building blocks' of rocks. They were taught about the different properties of certain minerals to how to use these properties to identify them. They used mineral kits and standard measures of identification, such as hardness tests, the streak test, color test, etc. They also learned about physical and chemical changes, erosion and weathering, on the Earth's surface.

<u>Scoring</u>

The inventories were scored using rubrics developed and refined in an earlier phase of the project. (See Appendix B.) 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

For each topic, two independent scorers scored the data 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 3. Inter-rater Reliability Scores Across Total Inventory Questions:

	Density	Pressure	Heat and Temperature	Geological Processes
First Round	r = .85	r = .91	r = .84	r = .88
Second Round	r = .91	r = .95	r = .91	r = .95
With Discussion	r = 1.00	r = 1.00	r = 1.00	r = 1.00

Results

The analysis compared the performance of five classes each receiving a different form of intervention: 1) students in the direct teaching of causal forms condition (CFDT) who were directly taught the causal forms in each unit; 2) students in the 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 the 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 the 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). A Tukey-Kramer HSD comparison showed no significant starting differences on initial scores between groups with negligible variance explained by intervention condition (R^2 = .06).

Did Students Make Gains in the Density Unit?

On the first unit, 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 pretest 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 (2, 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.

Did Non-Supported Isomorphic Transfer Occur?

The analysis next considered whether the gains in density would transfer to understanding of a second topic (pressure). There was evidence that the gains did transfer. Unlike the density pretest, the pressure pretest showed significant differences 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) suggesting that there may be some very small transfer effects already 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 (density pretest scores) were then plotted against pressure post-test scores in a multiple regression model (R^2 = .23). 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 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). The students with direct teaching only on the first topic (IFT) outperformed the control students who had no causal exposure (p < .05) with least squares means of 25.45 (SE = 1.14), 23.96 (SE = .79), and 21.56 (SE = .66) suggesting that students were able to transfer aspects of the causal intervention from unit one. These results offer evidence that there is some transfer from one topic to another when the embedded causal patterns are the same.

Figure 2.
Prediction Formula Detailing Parameter Estimates (Intervention Condition and Inventory Version) to Estimate Pressure Post-test Scores

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

Did Non-Supported, Non-Isomorphic Transfer Occur?

Next, we analyzed the data 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 from exposure to non-isomorphic causal forms. 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 on the post-test scores suggesting that non-supported, non-isomorphic transfer did not occur. The finding that there was no difference between the direct causal teaching group and the control group on the post-test performance suggested that the causal interventions in the heat and temperature (that were newly designed) may not be effective aside from questions of transfer. The research design allows us to tease out the effects of the transfer components versus the direct causal teaching components that occur within the unit by comparing the performance of the class that had causal teaching in units one and two but not three (CFI) to the class that had causal teaching in all three (CFDT). The lack of difference between those classes and the controls argues both that unsupported, non-isomorphic transfer did not occur and that the causal interventions in that unit did not result in significantly better performance.

Was There Evidence of "Preparation for Future Learning?"

Finally, there was some evidence that learning on a fourth topic, geological processes, where none of the students received any direct teaching of causality, showed some general transfer effects in the form of "Preparation for Future Learning." 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 just the first two units significantly outperformed the group that had causal teaching on the third unit only (CFI > NFO, (Abs(Dif) - LSD = 0.02, $p < .05$). This suggests that there may have been minimal effects of the causal intervention on learning more generally and that perhaps the students were better prepared for learning in the sense that they might attend to the causality involved.

This suggests that there may have been minimal effects of the causal intervention on learning more generally. This finding was in some respects surprising because of the lack of differences in student performance on the third unit and the fact that some of the causal forms inherent in the fourth topic, geological processes, are 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 to be highly tentative at this point and in need of further investigation.

Was There Persistence of Learning Across the Year?

Next we analyzed the year-end assessment to see if there was persistence of effects over the course of the year. The analyses compare students' performance on that portion of the unit test to those responses on the year-end test. The length of time between the unit and the year-end test varied with when the unit took place during the year. So therefore, the intervening subject matter also depends upon which part of the test is being analyzed.

The year-end analysis shows some interesting patterns. Students' post-test scores at the points in the year following the units significantly predicted students' retention scores at the end of the year, (F (1, 121) = 76.72, $p < .0001$, $R^2 = .39$). If one assumes that what is being tested is a matter of retention, one would expect students' performance would either be the same or go down slightly. However, students' performance actually went up slightly. A paired t-test revealed significant differences (t (121) = -2.39, p = .0091) with means of 10.98 (SD = 3.42) and 11.68 (SD = 3.77) between combined unit post-test score and year-end score, respectively. A number of interpretations are possible. There may be a re-test effect where students simply get better at answering the questions on the test. However, this is typically not the case with questions that students tend to have deep misconceptions about. Another possibility, one that favors our transfer hypothesis, is that as students become more familiar with the causal forms they should be able to apply them more effectively and more flexibly. Possibly students were able to detect the causal forms better on the year end assessment than the earlier post-tests because they had more experience with detecting and mapping causal forms and that this improved their facility with the forms. The pattern of results in the individual topics supports this interpretation. On the topic of density, the first topic where students learned about causality, students perform significantly better at the end of the year than right after the unit (although there were significant and substantive pre- to post-test gains), t (127) = -2.42, p = .0084, with respective means of 4.80 (SD = 1.43) and 5.16 (SD = 1.25). On the second topic, pressure, there were no significant differences between the post unit scores and the year-end retention scores, t (132) = -0.62, p = .2671. This might be predicted if one were to assume that having experienced relational causality in both density and pressure, students were well prepared to detect the opportunity and apply it to the pressure post-test. On the third topic, heat and temperature, students again perform significantly better at the end of the year than right after the unit (although there were significant and substantive pre- to post-test gains), t (131) = -1.86, p = .0325, with respective means of 3.66 (SD = 2.33) and 4.02 (SD = 2.47). In any case, the findings certainly offer evidence that the learning was persistent over the course of the year.

The students' interviews, conducted immediately following each unit, offer further insights into how students understood and applied the causal forms. A pattern that emerged in the interviews with students who were taught relational causal forms in the density unit, but not the pressure unit (IF group) suggested that they did not necessarily have an explicit awareness or reflective sense of how the causal forms applied in the second unit. So even though they did better in terms of transfer, they didn't appear to be explicitly aware that they were engaged in transferring the causality. This is not particularly surprising in that they were given no support for transfer or more generally for explicitly extracting the causal forms. In the interviews, it appeared that most students were figuring out how to map the causal forms as they explained them in the interview. For example, Sita, reasons through the relationships once the researcher asked 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."

Interviewer: "What are the two independent things in this case?"

Sita: "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 even if she isn't explicitly aware that she was doing so until the interviewer cued her to be sensitive to it.

Discussion of Study # 1 Results

To summarize the results of the first study generally, these results give a mixed picture for the unsupported transfer of causal forms but suggest that transfer is indeed possible. Broadly, it suggests that at least in the case of isomorphic forms, students can adopt the causal forms and transfer them to some extent. It appears that students have developed some tacit knowledge of causal forms, but have not necessarily abstracted it to apply it flexibly in new contexts. 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. 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 and facilitating 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.[i] 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.

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. We reasoned that students might think more flexibly in analyzing the inherent causality if they held a greater repertoire of causal forms. We noticed in Study #1 that occasionally students had difficulty fully grasping the causal forms. So for example, they sometimes confused additive forms of causality with relational forms, so they might say that you need two variables for a relational causality, but not realize that it is the relationship between the variables that matters as opposed to just the number of variables. Contrasting different forms should help students to better understand the distinct features of each form. Learning about causal forms in a variety of situations with very different surface features, should help the students extract the underlying deep structure (Gick & Holyoak, 1980, 1983). Further, if students generate their own analogies (Pittman, 1999), it forces them to seek out the similarity relations (Wong, 1993) increasing the likelihood of transfer. Engaging students in increased connection-making should support transfer.

Study #2 looked at what happened when we 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 considered what happens when students are given transfer support in either materials-based or teacher-guided contexts.

Study #2:

The comparisons for the second study were designed to address the following questions about transfer and persistence in supported contexts:

1. Does learning about specific causal patterns transfer from one topic to another when the embedded causal patterns are isomorphic?
2. Does learning about specific causal forms transfer from one topic to another when the embedded causal forms are non-isomorphic?
3. Does learning about specific causal forms enhance students' ability to learn science more generally--in terms of "Preparation for Future Learning" (Bransford & Schwartz, 1999)?
4. Are the gains that the students make in deeply understanding the science concepts persistent? Do they retain those gains by the end of the school year?

The second study examined supported transfer and compared materials-based support with materials-based plus teacher-facilitated support. The transfer support interventions were designed to increase students' sensitivity to opportunities for transfer and to assist with the mapping process. They encouraged both "low road" and "high road" transfer (Perkins & Salomon, 1988) techniques. This means that some techniques are aimed at changing behaviors (for instance, outlawing terms like "high" and "low" when taking about relational causality and encouraging explicitly relational terms such as "higher" and "lower" instead). Other techniques are designed to encourage high-level reflection to engage students in actively seeking transfer opportunities in a mindful way. Reflective abstraction was considered to be especially important because in Study #1, students appeared to use the causal knowledge in a somewhat tacit manner as discussed above. There were three primary components to the transfer supports that we designed: 1) broadening students' repertoire and grasp of different causal forms; 2) providing opportunities to explicitly map the analogical relationships so that students could develop the ability to transfer the causal forms; 3) enhancing students' metacognition as it applies to science learning in general and to causality specifically and offering opportunities to make connections on their own relating to the inherent causality to enhance their sensitivity to the possibilities for transfer.

Broadening Students' Understanding of the Nature of Causality

Broadening students' understanding and repertoire of different causal forms should enable them to think about the causality implicit in specific science topics more flexibly and increase the possibility that they will be sensitive to the presence of underlying causal structures. Certain causal forms are likely to be more easily grasped by students than others that may be more counter-intuitive or developmentally difficult without appropriate educational scaffolds (For a review, see Grotzer, 2003). For instance, students are likely to grasp domino forms of causality at an early age (Grotzer, 1989, 1993; Van Orden & Paap, 1997). Students have readily accessible experiences that relate to other forms which they can be made aware of, for instance, escalating causality in the lunchroom as students try to speak over each other and become louder and louder, additive forms of causality where a number of events accumulate in a specific outcome, and so forth. We decided that by exposing students to a variety of causal forms (See Appendix C.) and discussing them at the outset of the school year, it might increase students' ability to think flexibly about and subsequently transfer the causal forms that they learned as an inherent part of their science learning.

Providing Support for Mapping the Causal Forms

As discussed above, students need to be sensitive to the possibility that an analogical relation may exist, but they also need to be able to engage in mapping the relationship (Gentner, 1983). They need to detect relational similarities between the base problems and the target problems and know how each relates to the other. While we assumed that as students engaged in repeated examples of particular causal forms, they might become increasingly sensitive to the possibility of transfer, we also recognized that they might need support for making the actual mapping between base and target problems. Therefore, we included material support for the mapping specific causal forms to specific concepts. (See Appendix D.)

Metacognitive Components:

Many researchers (Blank, 2000; Georghiades, 2000; Hogan, 1999; Nickerson, Perkins, & Smith, 1985) have demonstrated the importance of mental management as a means to support the restructuring of ideas in science. Providing opportunities for students to formally reflect on their ideas may result in a more permanent restructuring of their scientific conceptions (Blank, 2000; Georghiades, 2000; Hogan, 1999).

Metacognition has been defined in a variety of ways and encompasses a variety of dimensions. Hennessey (1999) has outlined the following characteristics: 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. The study here adopts this definition and assumes that students need to be aware of their thinking and their ideas, need to monitor them and would benefit from heuristics to help them do so.

Another important aspect of metacognition is how it works within group contexts. Hogan (1999) argues that the aim of education is not to merely develop an individual's personal knowledge structures, but rather to engage students in disciplinary knowledge that is open for debate and criticism. 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. Students negotiate the status of their ideas in relation to other students or to universally held cultural assumptions on the way things work. For this research, we sought ways to support both individual and group metacognition to facilitate the transfer of causal understandings between topics.

We framed the metacognitive support (Mittlefehldt & Grotzer, 2003) by three categories of metacognition (see Table 4): intelligibility, wide-applicability, and plausibility on two levels: intrapersonal and interpersonal. The first category, "intelligibility," adopted from Beeth (1998), encompasses how students reflect on their ability to make sense of the content of thinking, as in when students ask themselves, "Does this make sense to me?" Students may reflect on others' ideas, (students', parents, teachers) and ask themselves, "How does the way that this person thinks about the idea help me make sense of it?" thus intelligibility works on both an intra-personal and interpersonal level.

The second category, "wide-applicability," encompasses how 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. Application is the mental testing of the potential solutions in attempt to apply the skill or conception to a new context. We used the term wide applicability to signal that the category is about connection-making in a broader sense than merely applying a concept as in near transfer, for example, recognizing that relational causality can help explain density differentials and pressure differentials.

The third category, "plausibility," also adopted from Beeth (1998), enables students to test their faith in a particular idea *visa via* alternative 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 it. This type of metacogntion involves being very self-aware of one's learning, questioning the learning, and holding a sense of skepticism about ideas.

We integrated these forms of metacognition into the transfer supports that we developed, both in the case of preparing students to be able to transfer concepts in future units (or transfer-forward support as in helping students develop flexible understandings in density that they might then apply to pressure) and to recognize opportunities and to actually enact transfer (or transfer-back support as in realizing that relational causality learned in density applies to pressure concepts and actually making the mapping).

How do these components translate in a more concrete sense? In all classes, students were introduced to "Good Science Thinking Moves" incorporating the metacognitive forms. Posters were hung in both teachers' classrooms listing moves in the following categories: 1) making connections, 2) questioning explanations, 3) engaging in self-reflection, 4) questioning the truth or believability of an idea, and 5) comparing your idea with others' ideas. Students were given concrete advice about how to engage in each category. For instance, "Try to think of examples that fit what you just learned"; "Try to think of examples that don't fit what you just learned"; "Ask yourself, does this make sense to me? What part of this idea makes sense to me? What do I find difficult about this idea?"; "Ask yourself, "How do other students' models help you think about ideas we've talked about? " and so on. Teachers introduced these moves to each of their classes early in the first unit. The moves were integrated into the curriculum materials for each unit. For example, on a materials-based support activity in density after being introduced to what causes differences in density at the microscopic level, students were encouraged to think about whether or not what they had learned made sense to them. The units also included explicit opportunities to engage in reflection that were teacher-guided for those students in the appropriate interventions as outlined below. 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.

Table 4: Metacognitive Tools: Context and Characteristic Questions

Metacognitive Forms	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 you? What might you add to have it make sense to you?
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 you think about other ideas we've talked about?
3. Plausibility	Intra-Personal	Do I believe this idea? Does this idea seem likely to be true?
	Inter-Personal	Do you believe Ian's model? Even if it makes sense to you, is there something about it that seems unlikely to be true? What is believable about it?

Methods

Design

We initially hoped to look at four classes, a control with no causal intervention throughout (CON Group), a causal control with causal intervention and no transfer support throughout (CF Group), a transfer support condition with causality and materials-based support condition (MB Group) and a transfer support condition with causality, materials-based support, plus teacher support (MBTS Group) throughout. However, in order to achieve balanced starting groups, we had to adjust our research design. We began by testing ten eighth grade science classes (five from each of two teachers) from the same suburban school system in the Boston area that participated in Study #1. In placing students in intervention conditions, we sought balanced groups so we used the density pre-test scores as a measure of starting level. We assessed and scored the data of all of the classes of two teachers so that we could create the most balanced groups. In so doing, we found that we had three classes for each teacher that offered balanced groups and showed no significant starting differences. The other classes were significantly higher or lower so these classes were not chosen to take part in the study.

We decided that the best design involved running six classes instead of four, but only three comparisons and that we would look at the CF, MB, and MBTS Groups balanced across teachers so that each condition had one class for each teacher. The trade-off was between running a straight control group, but adding an uncontrolled for teacher variable versus controlling for the teacher variable, but not running the straight control. Because we have seen some teacher differences (not in past causal outcomes but in teaching styles that might impact transfer) for these two teachers and because the earlier phases of research had already established that the causal forms groups outperform the straight controls, we decided to drop the straight controls. This study would allow us to assess whether we would see greater transfer with transfer support than we had already seen in Study #1 with the teaching of causal forms without transfer support.

We decided that the causal forms group should have some of the same introductory materials in the first unit as the transfer support groups, but not explicit transfer mapping components, and then no further support beyond the causal interventions in the remaining units. This variation made sense because the year one data had already established that there was some transfer with the causal forms teaching. Therefore, this group was treated much like the MBTS group for unit one. This created a causal group that had good transfer support for the first unit and then no transfer support for any of the following units. Therefore, we relabeled the group to CFwMBTS to keep them distinct from the straight causal forms group from Study one. We collapsed the CFwMBTS group into the MBTS group for the appropriate analyses below (those pertaining to unit one or assessing transfer from unit one to unit two. After that point, they are distinct in the analysis.) This mimics a scenario where teachers start out with a unit that addresses causality, metacognition, and transfer and then teach with some attention to causality but not the same attention to transfer throughout.

In addition to reworking the units from Study #1 to add metacognitive and causality-based transfer support, we also redesigned them so that we could test transfer at three points in learning: 1) on the pretest; 2) on an interim inventory that we added; and 3) on the post-test. The rationale for the change was as follows. In the first study, we were testing unsupported transfer, so we used the pretest scores as one measure of transfer. So for instance, we looked at whether the students in the density unit who had the causal intervention outperformed control students on the pressure pretest. We also looked at performance on the pressure post-test because the configuration of the comparison groups controlled for exposure to the causal intervention on the pressure unit (i.e. one group that had causal components on the density unit did not have them on the pressure unit, while another group had them on both.) This made it possible to measure whether exposure on an earlier unit enhanced students' ability to *learn* the causality on a later unit. For the second study, we reworked the units (starting with the second unit on pressure where we expected some transfer from density to be evident) so that the causal components with transfer support were offered in the second part of each unit and the first part simply offered good opportunities to learn the concepts minus any causal or transfer support. The students had essentially the same causal activities as in our previous research plus the transfer mapping components and added transfer discussions, but they were shifted into the second half of the units. We did this for the units that involved causal teaching after the first one (the pressure unit and the heat and temperature unit). (The last unit, Force and Motion, was the one where we tested for "Preparation for Future Learning Transfer" in a teacher taught unit, so it was not affected.)

We gave a pretest to assess, within each group, the possibility of spontaneous transfer. Then the teachers taught the subject matter using "best practices" science teaching (without causality and transfer support) and then we gave an interim assessment. We expected that students might recognize, without cueing or mapping support, the opportunity to transfer the causal forms learned in the earlier unit and that this would be revealed by the interim measure. The final portion of the unit involved introducing the causal pieces to all of the groups and the causal pieces with explicit transfer support in terms of cueing and mapping to the transfer intervention groups. Then students were given a post-test to measure transfer with explicit causal and transfer support. This reconfiguring of units also allowed us to look at students who had transfer support in previous units in unsupported conditions in the new units.

The specific units and the order in which they were taught in the second year followed the framework of the first study for the first three units. Teachers started with density, followed by pressure, and then heat and temperature. The final unit of the year was Force and Motion. This was also a change from Study #1 was mandated by changes in the school system. The change was made well into the school year and introduced an additional, unanticipated variable into the study

Table 5: Transfer: Experimental Groups for Study #2

	Group 1 - Causal Forms with MBTS for Unit One (CFwMBTS) (2 classes)	Group 2- Causal Forms with Materials-Based Transfer Support (MB) (2 classes)	Group 3- Causal Forms with Materials-Based plus Teacher-Supported Transfer Support (MBTS) (2 classes)
Unit 1 Density (Relational causal structure)	>Pre-assessment >Teaching of form #1 with intro to causality and metacognition support and transfer-forward materials-based plus teacher-supported support for unit 1 only >Post-assessment	>Pre-assessment >Teaching of form #1with intro to causality and metacognition support and transfer-forward materials-based support >Post-assessment	>Pre-assessment >Teaching of form #1with intro to causality and metacognition support and transfer-forward materials-based plus teacher-supported support >Post-assessment
Unit 2 Pressure (Relational causal structure)	>Pre-assessment >Teaching of unit concepts >Interim assessment >Teaching of form #1 >Post-assessment	>Pre-assessment >Teaching of unit concepts >Interim assessment >Teaching of form #1 with materials-based transfer support >Post-assessment	>Pre-assessment >Teaching of unit concepts >Interim Assessment >Teaching of form #1 with materials-based and teacher-supported transfer support >Post-assessment
Unit 3 Heat and Temperature (Domino, Re-entrant, Linear causal structures)	>Pre-assessment >Teaching of unit concepts >Interim assessment >Teaching of form- #2 >Post-assessment	>Pre-assessment >Teaching of unit concepts >Interim assessment >Teaching of forms- #2 with materials-based transfer support >Post-assessment	>Pre-assessment >Teaching of unit concepts >Interim assessment > Teaching of forms- #2 with materials-based and teacher-directed transfer support >Post-assessment
Unit 4 Force and Motion	>Pre-assessment >No intervention >Post-assessment	>Pre-assessment >No intervention >Post-assessment	>Pre-assessment >No intervention >Post-assessment
Year End Assessment	>Assessment revisiting questions from the above topics to evaluate the persistence of learning over the year.	>Assessment revisiting questions from the above topics to evaluate the persistence of learning over the year.	>Assessment revisiting questions from the above topics to evaluate the persistence of learning over the year.

from year one to year two. We made some adjustments to the heat and temperature unit between years one and two based on our year one data. The heat and temperature unit was a new unit and the data suggested that the causal components were not as effective as in other Understandings of Consequence units. Therefore, we analyzed difficulties in student understanding during year one and modified the unit accordingly.

We used essentially the same assessments as in Study #1. We omitted a couple of multiple choice questions that were uninformative. For the Force and Motion Unit, we used an inventory that we had previously designed and tested based on work in our earlier study (Bell, Carroll, & Grotzer, 2000) and incorporating items from Hestenes, Wells, and Swackhamer (1992). In addition to the pre-inventory prior to each unit and a post-inventory following each unit, and for the second and third units, an interim assessment halfway through the unit and prior to the teaching of the causal components or transfer support in that particular unit, we also interviewed a subset of students. 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.

We scored the data using the rubrics from Study #1. For Force and Motion, we used rubrics we had designed for an earlier phase in the study and refined them for use during this phase. For each topic, two independent scorers scored the data 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 6. Inter-rater Reliability Scores Across Total Inventory Questions: Study Two

	Density	Pressure	Heat and Temperature	Force and Motion	Year End Assessment
First Round	r = .75	r = .92	r = .93	r = .88	r = .88
Second Round	r = .91	r = .97	r = .96	r = .96	r = .97
With Discussion	r = 1.00	r = 1.00	r = 1.00	r = 1.00	r = 1.00

Results

The comparisons in the second year were designed to assess the impact of supported causal transfer. We compared the following groups: 1. CFwMBTS (causal forms with materials-based and teacher transfer support in unit one only); 2. MB (causal forms with materials-based transfer support throughout); and 3. MBTS Groups (causal forms with materials-based and teacher transfer support throughout) balanced across teachers so that each condition had one class for each teacher. In the course of the analysis, as explained below, we also made some comparisons to our straight controls and to our causal form classes from the previous study as further evidence in support of the interpretations. This was an imperfect solution but seemed the best option given the constraints imposed by the real world conditions.

Did Students Make Gains in the Density Unit?

First, we assessed whether or not learning took place that could potentially transfer from the first unit (density) to the second unit (pressure). There were significant and substantive gains from pre- to post-test *across* the three intervention conditions on the density assessments (t (125) = -30.08, $p < .0001$, Pretest $M = 8.06$ $SD = 2.25$, Range = 3.16-16.00; Post-test $M = 15.38$, $SD = 2.47$, Range = 6.20-20.30). There were also significant and substantive pre- to post-test gains *within* each group. Recall that for the first unit, students in the causal forms group also received materials-based plus teacher-support for learning about the nature of causality and for engaging in metacognition. This analysis collapses the CFwMBTS and MBTS groups because they have the same treatment in the initial unit. For the CFwMBTS and MBTS Groups: (t (87) = -23.32, $p < .0001$, Pretest $M = 8.27$, $SD = 2.56$, Range = 3.17-16.00; Post-test $M = 15.44$, $SD = 2.52$, Range = 6.17-20.33); For the MB Group: (t (39) = -19.70, $p < .0001$, Pretest $M = 7.63$, $SD = 1.33$, Range = 5.17-10.50; Post-test $M = 15.27$, $SD = 2.38$, Range = 8.67-19.33).

The finding that students in both groups show significant and substantive pre- to post-test gains makes sense. The causal curriculum has been shown to be effective. In this instance, we are using the causal curriculum but bolstering the likelihood that it will transfer. Of course, it was possible that adding reflective and metacognitive components to the curriculum could be burdensome and overwhelm the focus on understanding goals. The results suggest that this did not happen. There were no significant differences between the transfer intervention groups on the post-test or on the students' gain scores. This suggests that the materials-based and materials-based plus intervention conditions did not differentially impact students' performance on the density post-test with the students in different groups performing equally well.

Did Supported Isomorphic Transfer Occur?

In the second unit, pressure, *across* groups, there were significant gains from pre- to mid-test: (t (116) = -7.27, $p < .0001$, Pretest $M = 10.79$, $SD = 2.81$, Range = 6.00-18.50; Mid-test $M = 12.51$, $SD = 3.34$, Range = 6.00-18.50). The pre- to mid-test gain reveal what students are able to figure out from subject matter teaching without any causal components and no transfer support. This suggests that students did figure out a fair amount on their own and suggests that some transfer of causal understanding took place.

There were also significant gains from mid-test to post-test (t (125) = -12.04, $p < .0001$, Mid-test $M = 12.51$, $SD = 3.34$, Range = 6.00-18.50; Post-test $M = 15.87$, $SD = 2.95$, Range = 8.00-18.50). The mid-test to post-test gains reveal what students were able to do after they had direct causal teaching (in the CFwMBTS Group) or direct causal teaching plus transfer support (MB and MBTS Groups). This shows that they make additional gains. This is not unexpected given the effectiveness of the causal teaching in previous years. Within the CFwMBTS and MBTS groups, the mid- to post-test gains are significantly larger than the pre- to mid-test gains (t (40) = -3.28, $p < .0011$and t (39) = -2.378, $p < .0115$,), pre- to mid-test gain $M = 1.03$, $SD = 2.68$, and $M = 2.01$, $SD = 2.40$; mid- to post-test gain $M = 3.58$, $SD = 3.21$ and $M = 2.73$, $SD = 2.78$, respectively CFwMBTS and MBTS groups). This underscores the effectiveness of the direct causal teaching (since the CFwMBTS had causal teaching, but no transfer support in between the mid- and post-test). However, it is important to note that students made significant gains in both instances.

The story of transfer can also be gleaned in part by the amount of variance explained in sets of scores by other scores. If the curriculum in the first unit had a substantive impact on students' understanding, then one would expect pretest scores to account for a modest amount of the variance in post-test scores. This does turn out to be the case. Across the groups, density pretest scores are significant (F (1, 125) = 15.83, $p < .0001$) but modest predictors ($R^2 = .11$) of density post-test scores. However, if learning during the density unit transfers to new topics, one would expect to see somewhat greater variance in the pressure pretest explained by the density post-test (though still a modest amount given that it is a new topic) and even greater variance explained in the pressure mid-test by the density post-test and pressure pretest. This trend can be found in the data. The density post-test is a significant predictor (F (1, 116) = 37.68, $p < .0001$) of the pressure pretest scores ($R^2 = .25$) and a significant predictor of the pressure mid-test scores (F (1, 126) = 52.31, $p < .0001$, $R^2 = .29$). Further, the pressure pretest scores are a significant predictor of performance on the pressure mid-test (F (1, 119) = 87.60, $p < .0001$) explaining a good amount of the variance ($R^2 = .43$). This was especially so within the groups that had teacher and materials-based support for unit one (F (1, 80) = 77.10, $p < .0001$, $R^2 = .49$) and less so in the group that had only materials-based support (F (1, 38) = 13.02, $p < .0009$, $R^2 = .26$). This gradual increase in variance accounted for makes sense both in terms of subject matter and causal content taught. Understanding density should help students understand pressure as the concepts are linked. They share a causal structure –relational causality. Applying those understandings to the pressure pretest and during the first half of the unit should explain a good amount of variance in the mid-test scores. This supports a transfer argument. It also makes sense that the pressure pretest scores would have more predictive value for the pressure mid-test scores than the density post-test scores given that they address the subject matter in addition to the causal structure.

The story in the amount of variance explained also supports the finding reported in the means above--that significant learning continues to take place during the second half of the pressure unit. Pressure pretest is a moderate predictor of performance on the post-test (F (1, 118) = 24.84, $p < .0001$, $R^2 = .18$.) and mid-test is a fairly good predictor of performance on the pressure post-test (F (1, 126) = 39.12, $p < .0001$, $R^2 = .23$) suggesting that in each case, some learning has carried over from the density unit but that the variance drops from mid-test to post-test, the interval during which the causal teaching and other transfer components took place.

One could argue that the gains experienced during the pre- to mid-portions of the unit are due to subject matter teaching rather than the transfer effects of the causal teaching. While the variance explained by the scores and the extent of the gains argue for a transfer interpretation, we conducted the following analysis to offer a means to calibrate the gains.

We included the two classes of control subjects and two classes that received direct causal teaching in at least the first two units (CFI and CFDT groups) from year one in the analysis. This gave five approximately equivalent sized groups (N = 47, 44, 46, 44, and 44) representing increasing levels of support as follows:

1. Control Group (CON)– "Best practices" teaching of science concepts with NO causal intervention.
2. Causal Forms Group (CF)- (CFI and CFDT from Study #1) Causal teaching in both units with no transfer support.
3. Causal Forms with MBTS in Unit 1 (CFwMBTS)-Causal teaching in both units with materials-based and teacher transfer support in unit one only.
4. Materials-Based Group (MB)- Causal teaching with materials-based transfer support in both units.
5. Materials-Based with Teacher Support Group (MBTS)- Causal teaching with materials-based and teacher transfer support in both units.

We contrasted the performance of these groups on portions of the assessments that students in both years participated in (overlapping questions on the pre- and post-tests).

These groups were not aligned for initial performance and it turned out that on the density pretest, the CF Group performed significantly higher than the CFwMBTS and MB groups on a Tukey-Kramer HSD test (CF > CFwMBTS and MB, (Abs(Dif) - LSD = 0.23, 0.62, respectively, $p < .05$). (See Figure 3.) However, by the density post-test, all of the causal groups significantly outperformed the control group (CF, CFwMBTS, MB, and MBTS > CON (Abs(Dif) - LSD =

1.92, 1.99, 1.86, 1.82, respectively, p <.05). (See Figure 4 and Table 7.) As would be expected, there were no significant differences between the post-test performances of the causal groups. All of the causal groups gained significantly more than the control group (CF, CFwMBTS, MB, and MBTS > CON (Abs(Dif) - LSD = 1.08, 2.48, 2.73, 1.73, respectively, p <.05). The MB group gained significantly more than the CF group (MB > CF (Abs(Dif) - LSD = 0.12, p <.05) by a negligible amount. It can be argued that they had further to gain given the significant difference in pretest scores and lack of significant difference in post-test scores.

Figure 3. Density Pretest Scores by Intervention Condition.

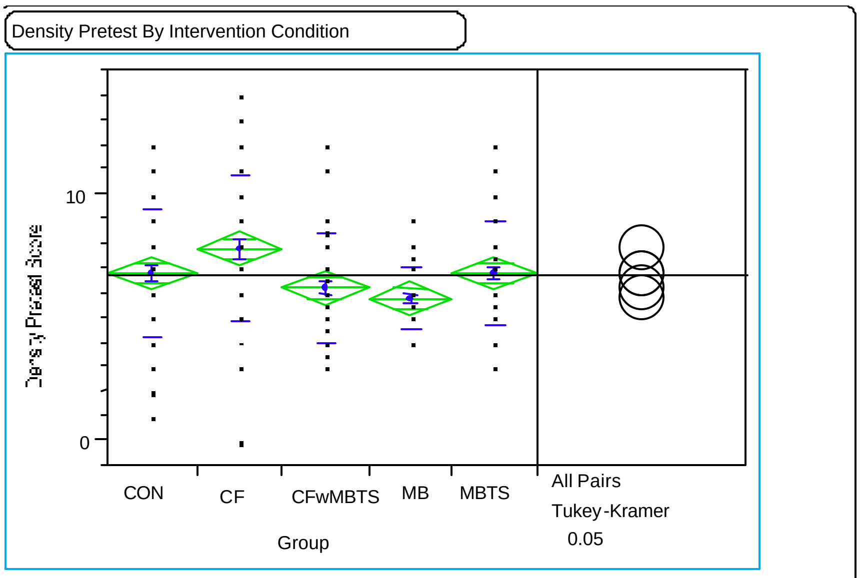


Figure 4. Density Post-test Scores by Intervention Condition

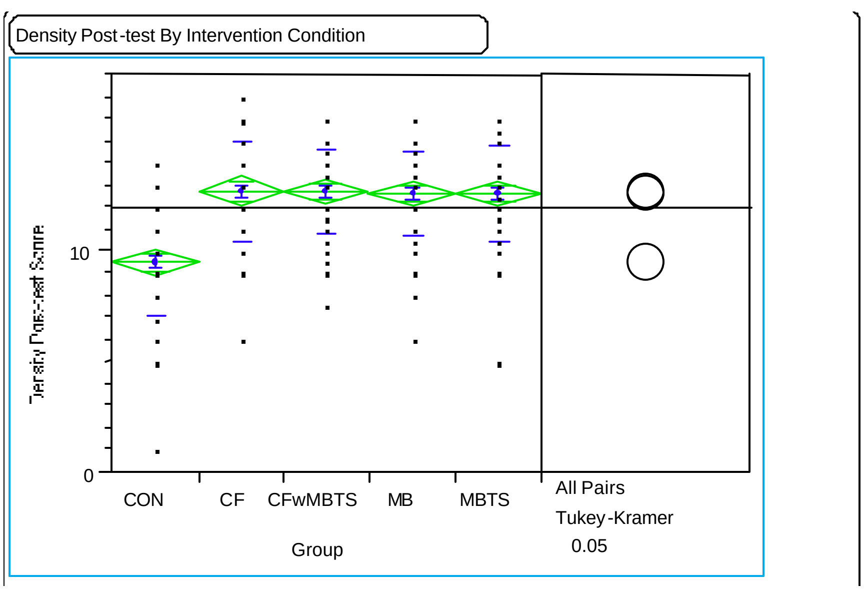


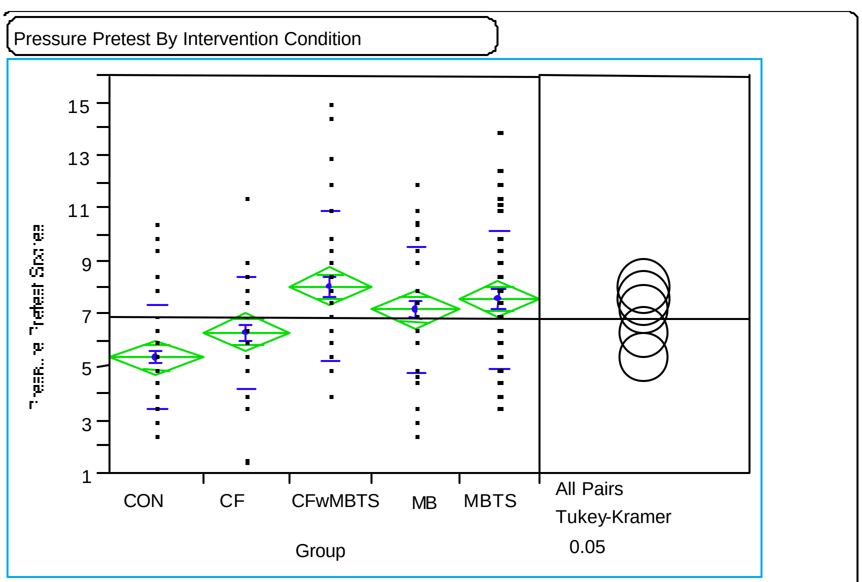
Table 7. Unit 1: Density Scores

	Control		CF		CFwMBTS		MB		MBTS	
	M	SD	M	SD	M	SD	M	SD	M	SD
Pretest	6.83	2.67	7.80	3.01	6.21	2.25	5.80	1.28	6.77	2.15
Post-test	9.49	2.53	12.71	2.31	12.76	1.92	12.64	1.97	12.60	2.23
Gain Score	2.62	2.28	5.19	2.93	6.57	2.57	6.83	2.06	5.84	2.66

In keeping with the argument above about the amount of variance explained, it is interesting to note that the density pretest explains a good portion of the variance in the density post-test scores in the Control group ($\underline{F}$ (1, 44) = 27.73, $\underline{p} < .0001$, $\underline{R}^2 = .39$), less in the Causal Forms Group ($\underline{F}$ (1, 40) = 5.70, $\underline{p} < .0219$, $\underline{R}^2 = .13$) and negligible amounts in the causality with transfer support groups: MB Group (F (1, 41) = 3.41, $\underline{p} < .0721$, $\underline{R}^2 = .08$.) and the CFwMBTS Group collapsed with the MBTS Group (F (1, 86) = 5.98, $\underline{p} < .0165$, $\underline{R}^2 = .07$.)

These findings underscore the effectiveness of the causal curriculum, but what about the students' ability to transfer what the benefits of the causal intervention to the second unit? Transfer differences already show on the pressure pretest. (See Figure 5.) All the groups perform significantly higher than the Control group except the CF group (CFwMBTS, MB, and MBTS > CON (Abs(Dif) - LSD = 1.27, 0.46, 0.80, respectively, $\underline{p} < .05$). (A puzzle here is that in the Study #1 analysis, the causal groups outperformed the control students on the pressure pretest. We think that the discrepancy is due to two factors: the year one analysis also included the class that had causal teaching on unit one only (IFT) and the loss of power due to the additional comparisons in the second analysis.) By the pretest, one of the transfer-supported groups (CFwMBTS) is already performing significantly higher than the straight causal forms group by a very small amount (CFwMBTS > CF, (Abs(Dif) - LSD = 0.26, respectively, $\underline{p} < .05$).

Figure 5. Pressure Pretest Scores by Intervention Condition.



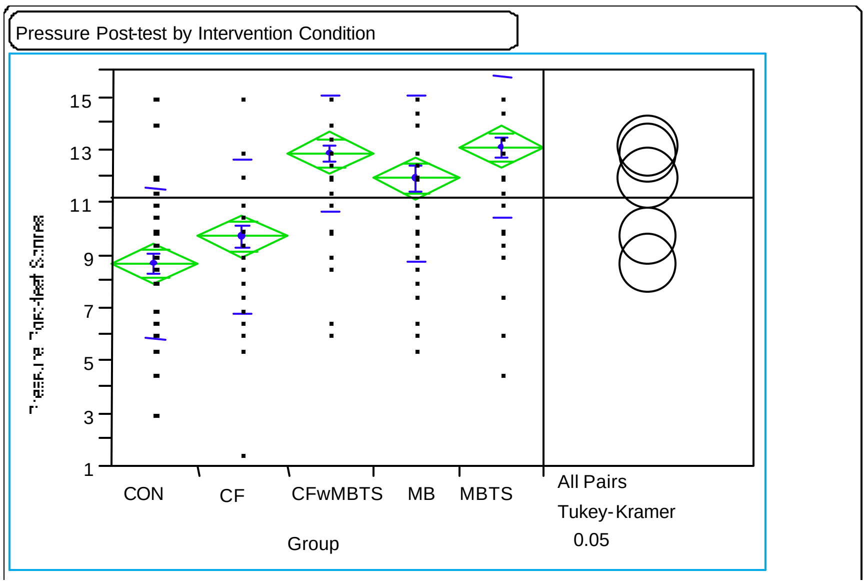
By the pressure post-test, all of the transfer component groups are performing significantly higher than the controls and the causal forms group (CFwMBTS, MB, and MBTS > CON (Abs(Dif) - LSD = 2.55, 1.56, 2.70, respectively, $\underline{p} < .05$) and (CFwMBTS, MB, and MBTS > CF (Abs(Dif) - LSD = 1.56, 0.57, 2.70, respectively, $\underline{p} < .05$). (See Figure 6 and Table 8.) The lack of a significant difference between the controls and causal group ($\underline{M}$ = 8.72, $\underline{SD}$ = 2.92; $\underline{M}$ = 9.71, $\underline{SD}$

= 2.95) again departs from the findings last year where they were part of a larger causal group and in a study with fewer comparisons at this point in the analysis (so subsequently less stringent than a Tukey-Kramer HSD which controls the p value across the multiple comparisons).

Table 8. Unit 2: Pressure Scores

	Control		CF		CFwMBTS		MB		MBTS	
	M	SD	M	SD	M	SD	M	SD	M	SD
Pretest	5.37	1.98	6.33	2.16	8.06	2.90	7.24	2.38	7.60	2.63
Post-test	8.72	2.92	9.71	2.95	12.92	2.28	11.94	3.16	13.09	2.74
Gain Score	3.20	2.76	3.45	2.61	4.83	2.92	4.76	2.65	5.44	3.10

Figure 6. Pressure Post-test Scores by Intervention Condition



This argues strongly that transfer did take place and that the transfer supports were effective. However, one further objection might be that the pre- to post-test scores in the CF, CFwMBTS, MB, and MBTS groups also includes the effects of the causal interventions that were taught throughout the unit for the CF group and in the second half of the unit for the groups from year two. (The pretest comparisons address this issue somewhat.) The interim assessment was included to reveal whether transfer effects would take place with just subject matter teaching (comparable to what the control group received for the entire unit) before the causal and transfer components in the second unit were taught. Therefore, we decided to compare performance on the pressure mid-test for the causal groups with transfer support to performance on the pressure post-test for the control group. This matches the type of exposure in the relevant part of the pressure unit for all of the groups (just good subject matter teaching), however, it is a stringent test of the hypothesis because the control group received twice as much teaching time. The CF group was left out of this analysis because it received causal teaching throughout the unit (as per the design in year one.) A Tukey-Kramer HSD test revealed that the groups that had causal teaching with materials-based and teacher-supported transfer in the density unit significantly outperformed (using their mid-test scores) the control students (using their post-test scores) (CFwMBTS collapsed with MBTS > CON (Abs(Dif) - LSD = 0.08. respectively, $p < .05$, M = 10.09, SD = 3.03 and M = 8.72, SD = 2.92, respectively). The mean of the materials-based transfer support group (M = 9.49, SD = 2.78) was not significantly different from either mean.

The performance of the CFwMBTS and MBTS groups echoes the finding from year one where the group with causal teaching in unit one and not in unit two continued to outperform the controls. It also argues that the differences in pressure post-test performance cannot be attributed merely to the confounding factor (that is necessarily part of the design) of teaching by revisiting concepts--once without causality and transfer and then revisiting them with causality and transfer.

Were there Differences between the Levels of Support for Isomorphic Transfer?

What about the different intervention conditions? How effective does each appear to be in terms of transfer? The finding above that the materials-based plus teacher support group is significantly higher on the mid-test than the controls on the post-test and that the materials-based support group is not significantly different from either hints that the addition of teacher support might be helpful. Here we examine this data more fully.

Within each group, there are significant gains from the pressure pre- to mid-test (collapsing the CFwMBTS with MBTS as they were for Unit 1: (t (80) = -5.29, p < .0001, Pretest M = 10.93, SD = 3.02, Range = 6.00–18.50; Mid-test M = 12.45, SD = 3.52, Range = 6.00- 18.50). MB Group: (t (38) = -5.14, p < .0001, Pretest M = 10.49, SD = 2.35, Range = 6.50 -15.50; Mid-test M = 12.63, SD = 2.97, Range = 7.25 – 18.50)). There are also significant gains from mid-test to post-test within each group (separating the CFwMBTS and MBTS groups as they were given differential treatment in the second half of the pressure unit): CFwMBTS Group: (t (43) = -7.41, p < .0001, Mid-test M = 12.41, SD = 3.67, Range = 6.00-18.50; Post-test M = 16.12, SD = 2.49, Range = 8.50-18.50); MB Group: (t (40) = -6.27, p < .0001, Mid-test M = 12.63, SD = 2.97, Range = 7.25 – 18.50; Post-test M = 15.11, SD = 3.37, Range = 9.00-18.50); MBTS Group: (t (41) = -7.21, p < .0001, Mid-test M = 12.49, SD = 3.40, Range = 6.00-18.50; Post-test M = 16.39, SD = 2.86, Range = 8 –18.50).

Based on Tukey-Kramer HSD tests, there are no significant differences in the pressure pretest scores between the three groups (M = 11.35, SD = 3.08; M= 10.49, SD = 2.35; and M = 10.50, SD= 2.94, for the CFwMBTS, MB, and MBTS groups, respectively). From pre- to mid-test, there are no differences in gains between the groups (F (2, 119) = 2.36, p = .0985 (M = 1.03, SD = 2.68; M= 2.19, SD = 2.66; and M = 2.01, SD= 2.40, for the CFwMBTS, MB, and MBTS groups, respectively). This makes sense given that the intervention conditions did not make a difference on the density post-test. It appears that the groups were equally well prepared to transfer causal learning and to learn pressure subject matter. From mid-test to post-test, there are no significant differences (F (2, 126) = 1.14, p = .2476) in the gains between the CFwMBTS (M = 3.58, SD = 3.21), MB (M = 2.73, SD= 2.78) and MBTS (M = 3.84, SD = 3.45) groups. These results suggest that each of the interventions is equally effective in enabling isomorphic transfer and that the comparison above between the transfer groups' mid-test and control group's post-test scores may hint at differences that cannot be detected in this sample size.

Did Non-Isomorphic Transfer Occur?

The students' performance on the Heat and Temperature unit shows significant pre- to mid- and mid- to post-test improvement though in some respects is less substantive than gains on other topics, despite the modifications to the causal components of the unit. This fits with our findings in Study #1.

Across the transfer supported groups, there were significant gains from pre- to mid-test: (t (115) = -12.53, p < .0001, Pretest M = 10.31, SD = 3.97, Range = 1.50-21.00; Mid-test M = 16.61, SD =

4.50, Range = 6.25-27.00). There were also significant gains from mid-test to post-test (t (123) = -3.26, p < .0007, Mid-test M = 16.61, SD = 4.50, Range = 6.25-27.00); Post-test M = 17.62, SD = 4.70, Range = 5 –27.00).

Figure 7. Heat and Temperature Pretest Scores by Intervention Condition (Transfer Collapsed)

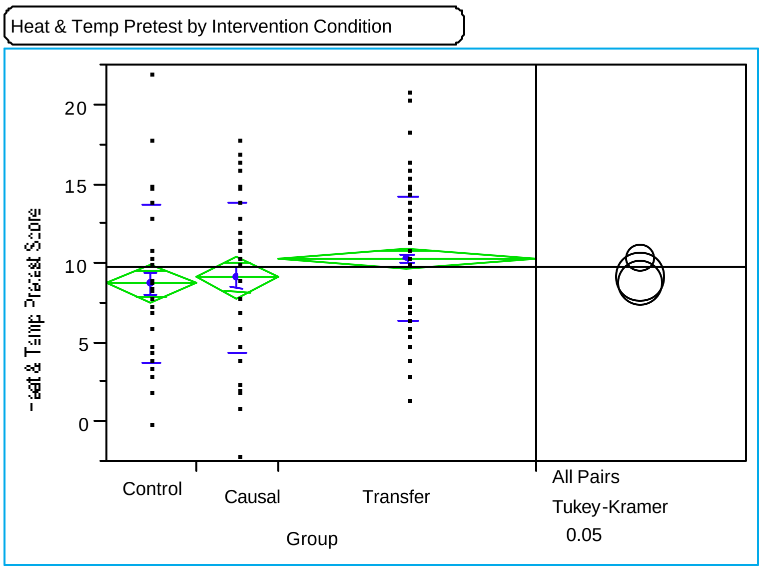
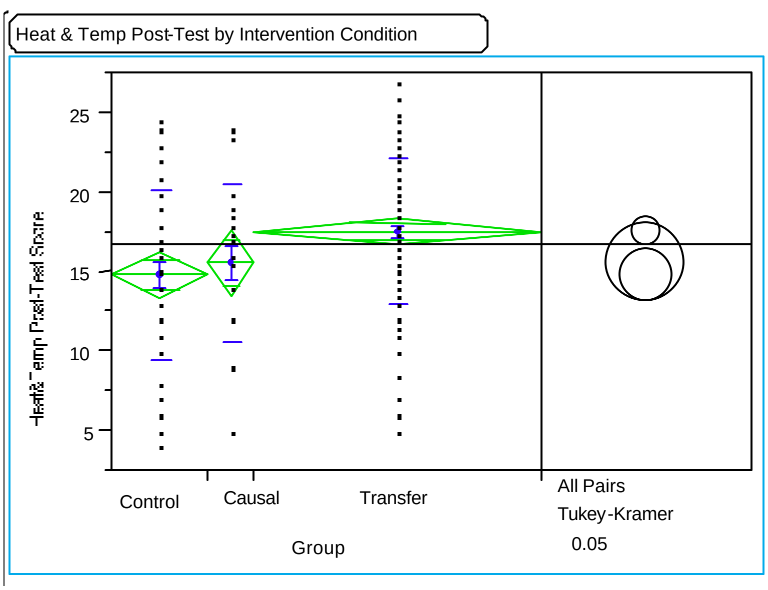


Figure 8. Heat and Temperature Post-test Scores by Intervention Condition (Transfer Collapsed)



The significant pre- to mid-test gains suggest that transfer did take place, but again, it is helpful to calibrate these gains against the gains of the control group and the causal group (from year one). Recall that all of the groups last year also made significant pre- to post-test gains on the heat and temperature assessments (across groups: (t (124) = -12.66, p < .0001) and within groups, of particular interest, the control group, (t (42) = -7.15, p < .0001) Pretest M = 8.72, SD = 5.01; Post-test M = 14.54, SD = .81). Therefore, we made the following comparisons. We looked at the performance of the controls, causal, and the transfer groups (collapsed into one group) on the heat and temperature pretest to see if there were any differences in performance. The means are in the predicted direction (Control: M= 8.72, SD = 5.01; Causal: M = 9.13, SD = 4.85; Transfer: M = 10.31, SD = 3.97) and the main effect of intervention condition approaches significance (F (2, 206) = 2.62, p = .07). (See Figure 7.) However, no significant differences are found between the means on the Tukey-Kramer HSD test. However, on the heat and temperature post-test, the transfer groups (collapsed) perform significantly higher than the control group as determined by a Tukey-Kramer HSD test (Transfer > CON (Abs(Dif) - LSD = 0.73, p <.05; Transfer M = 17.62, SD = 4.71; Control M = 14.86, SD = 5.43). (See Figure 8.) The CF group (using only those students with direct causal teaching throughout (CFDT) from last year) is not significantly different from the transfer group (Causal M = 15.55, SD = 5.08; Transfer M = 17.62, SD = 4.71) though they are in the expected direction.

We also did a stringent test looking at the difference between the performance of the transfer groups on the mid-test (prior to any direct causal teaching or related transfer in the heat and temperature unit) to the control group's performance on the heat and temperature post-test, as we had with the pressure test scores. Again, this confers the advantage of twice as much learning time in the heat and temperature unit to the control group. The groups are significantly different (F (1, 170) = 4.42, p = .0369) with the transfer groups performing higher (M = 16.61, SD = 4.50) than the control group (M = 14.86, SD = 5.43). This argues that they were better prepared for learning about heat and temperature from standard teaching than were the controls. One critique of this explanation might be that we did make slight modifications to the heat and temperature unit and it is possible that those changes account for the gains rather than transfer effects. However, the post-test scores of the CF group are not significantly different from the transfer groups' scores, as elaborated above, (using only those students with direct causal teaching throughout (CFDT) from last year). Recall, too, that there were no significant differences between the controls and the CF students on the heat and temperature post-test last year. Taken together, this offers further evidence that the transfer plus causal intervention accounts for at least some of the difference between the controls and transfer groups.

Even though there was significant improvement from mid- to post-test, it is not as substantive as gains in other units. This suggests that the causal interventions may have less impact. What is going on in Heat and Temperature to account for some of the lack of improvement from mid- to post-test? We analyzed the components of the Heat and Temperature assessment to get a better sense of what was happening. We found that students did make substantive gains on understanding the causal patterns involved in heat and temperature (domino, re-entrant, and linear causal structures). This was so *across* (t (123) = -4.38, p < .0001, Mid-test M = 7.00, SD = 2.32, Range = 1.00-11.00; Post-test M = 7.75, SD = 2.23, Range = 1.00-11.00) and *within* groups: CFwMBTS Group: (t (44) = -2.57, p = .0068, Mid- test M = 6.91, SD = 2.38, Range = 2.25-11.00; Post-test M = 7.70, SD = 2.38, Range = 2.00-11.00); MB Group: (t (38) = -2.67, p = .0055, Mid-test M = 6.78, SD = 2.25, Range = 1.00-11.00; Post-test M = 7.45, SD = 2.25, Range = 1.00-11.00) and MBTS Group: (t (39) = -2.29, p = .0137, Mid-test M = 7.35, SD = 2.36, Range = 2.00-11.00; Post-test M = 8.12, SD = 2.04, Range = 3.00-11.00). However, they did not make significant gains from mid-test to post-test on understanding causal mechanism (that kinetic energy or movement of molecules is responsible for the transfer of heat rather than substance notions of heat flowing, for instance.) This was so *across*: (t (118) = -1.23, p = .1210, Mid test M = 6.98, SD = 2.39, Range = 1.00-13.00; Post-test M = 7.15, SD = 2.61, Range = 1.00-13.00) and *within* groups: CFwMBTS Group: (t (39) = -57, p = .2856, Mid-test M = 6.84, SD = 2.39, Range

= 1.00-13.00; Post-test M = 6.99, SD = 2.96, Range = 1.00-13.00; MB Group: (t (38) = -.20, p = .4195, Mid-test M = 6.81, SD = 2.16, Range = 2.00-11.00; Post-test M = 6.70, SD = 2.33, Range = 2.00-11.00; MBTS Group: (t (39) = -1.17, p = .1253, Mid-test M = 7.30, SD = 2.56, Range = 1.00-13.00; Post-test M = 7.79, SD = 2.37, Range = 3.5-13.00).

In terms of transfer, these findings make sense. The transfer components focused much more on causal patterns of interaction (domino, relational, re-entrant, and so on) from the outset of the school year. These are also more easily generalized than the particular deep level mechanisms in each phenomenon to be explained. Therefore, it makes sense that understanding of causal pattern may transfer more easily than understanding of causal mechanism.

Were there Differences between the Levels of Support for Non-Isomorphic Transfer?

Within each of the transfer support groups, there are significant pre- to mid-test gains: CFwMBTS Group: (t (42) = -6.91, p < .0001, Pretest M = 10.92, SD = 4.14, Range = 4.00-21.00; Mid-test M = 16.31, SD = 4.70, Range = 6.25-26.00); MB Group: (t (34) = -7.03, p < .0001, Pretest M = 9.67, SD = 4.25, Range = 1.50 -18.50; Mid-test M = 16.18, SD = 4.02, Range = 8.00 –23.00); and MBTS Group: (t (37) = -7.78, p < .0001, Pretest M = 10.29, SD = 3.38, Range = 3.00–18.50; Mid-test M = 17.38, SD = 4.74, Range = 7.00-27.00). There are also significant, but less substantive gains within groups from mid-test to post-test: CFwMBTS Group: (t (44) = -1.88, p < .0330, Mid-test M = 16.31, SD = 4.70, Range = 6.25-26.00; Post-test M = 17.39, SD = 5.41, Range = 5.00-26.00); MB Group: (t (38) = -1.91, p < .0386, Mid-test M = 16.18, SD = 4.02, Range = 8.00–23.00; Post-test M = 16.84, SD = 4.45, Range = 5.00-24.00); and MBTS Group: (t (39) = -1.35, p < .0320, Mid-test M = 17.38, SD = 4.74, Range = 7.00-27.00; Post-test M = 18.68, SD = 3.99, Range = 11.00 –27.00).

All of the transfer groups appear to fare equally well. There are no significant differences in pressure pretest scores between the three groups (M = 10.92, SD = 4.21; M= 9.67, SD = 4.25; and M = 10.29, SD= 3.38, for the CFwMBTS, MB, and MBTS groups, respectively). From pre- to mid-test, there are no significant differences in the gains between the groups (M = 5.35, SD = 5.08; M= 6.30, SD = 5.30; and M = 7.18, SD= 5.69, for the CFwMBTS, MB, and MBTS groups, respectively) although the mean scores fall in a pattern that one would predict given the level of transfer support. From mid-test to post-test, there are no differences in gains between the groups (M = 1.15, SD = 4.09; M= 1.08, SD = 3.70; and M = 1.35, SD= 4.48, for the CFwMBTS, MB, and MBTS groups, respectively). These findings suggest that there are no measurable differences in the types of transfer support and that materials-based support may be as effective as materials-based plus teacher support.

Did Transfer in the Form of Preparation for Future Learning Occur?

Students' performance on the Force and Motion unit informs whether transfer in the form of "Preparation for Future Learning" occurred. Recall that in this unit, there were no interventions of any kind. The students participated in teacher-taught units and took pre- and post-tests before and after the unit. Across the transfer supported groups, there were significant gains from pre- to post-test: (t (126) = -10.42, p < .0001, Pretest M = 12.14, SD = 2.71, Range = 4.00-17.50; Post-test M = 14.87, SD = 2.57, Range = 6.00-18.00). Within each group, there were significant gains from pre- to post-test: CFwMBTS Group: (t (43) = -5.58, p < .0001, Pretest M = 12.41, SD = 2.98, Range = 4.00- 17.00; Post-test M = 14.71, SD = 2.73, Range = 6.00-18.00); MB Group: (t (40) = -5.15, p < .0001, Pretest M = 12.17, SD = 2.85, Range = 6- 17.50; Post-test M = 14.90, SD = 2.62, Range = 9.50-18.00); and MBTS Group: (t (41) = -7.73, p < .0001, Pretest M = 11.81, SD = 2.24, Range = 7- 16.50; Post-test M = 15.02, SD = 2.38, Range = 8.00-18.00). There were no significant differences between the different types of transfer groups on pretest or post-test means. Unfortunately, our plan to contrast the performance of these groups to the previous control group fell apart when the school changed the unit between years one and two. In light of this unanticipated change, our decision to not run a straight control group turned out not to be the best strategy because it leaves us unable to generate more conclusive findings (than those last year) about PFL transfer. In retrospect, it is easy to second guess the choice and argue for running one kind of transfer group and one straight control. However, at the time, we felt that this would be a replication of data. Also, in the reality of schools, once teachers see something as effective (as they do the causal interventions) it becomes increasingly difficult to justify involving some students and not others. Given that we thought we would be able to make clear comparisons to the control group we had already run, we didn't see the tradeoffs as arguing for running another one.

Was There Persistence of Effects Across the School Year?

Again, we gave a year-end assessment to measure the persistence of effects. Students' post-test scores at the points in the year following the units significantly predicted students' retention scores at the end of the year, (F (1, 119) = 111.25, $p < .0001$, $R^2 = .48$). Unlike in year one, across the groups, there were no significant differences between the unit test responses and the year end responses: For Density: (t (125) = 3.24, p = .9992, Unit Test M = 5.16, SD = 1.30, Range = 1.00-6.00; Year-End Test M = 4.72, SD = 1.62, Range = 1.00-6.00); For Pressure: (t (127) = 5.47, p = 1.0000, Unit Test M = 3.89, SD = 1.30, Range = 1.00-5.00; Year-End Test M = 3.29, SD = 1.53, Range = 1.00-5.00); For Heat and Temperature: (t (130) = -1.04, p = .1503, Unit Test M = 5.33, SD = 2.13, Range = 0-8.00; Year-End Test M = 5.42, SD = 2.00, Range = 0-8.00). There were no significant differences in how the groups performed (CFwMBTS M = 10.43, SD = 3.19; MB = M = 10.84, SD = 3.22; MBTS M = 10.96, SD = 2.71) and the within group results echoed the across groups results. These findings argue that students retained the learning that they did during the year, but that neither were there gains in how they performed (which would have been additional evidence of transfer).

Results Summary and Discussion

Both studies replicate the findings in the earlier research on the effectiveness of teaching about causal forms. The results here suggest that students are able to transfer some of those gains to the learning of new topics. In the case of unsupported transfer of causal forms, the results give a mixed picture, but suggest that unsupported transfer is indeed possible.

1. There is modest evidence that unsupported isomorphic transfer did occur. The students who had causal teaching in unit one (density) but not in unit two (pressure) performed just as well as students with direct causal teaching throughout on unit two and significantly higher than controls.
2.There was no evidence of unsupported non-isomorphic transfer.
4. There appeared to be some evidence for transfer in terms of "Preparation for Future Learning" (PFL).
5. There is clear persistence of learning during the year and in some cases, student scores were significantly higher at the end of the year than at the end of the unit.
6. There was evidence of persistence of learning two years later.

In the case of supported transfer of causal forms:
1. There is clear evidence for supported, isomorphic transfer.

2. Materials-based and materials-based plus teacher-supported transfer appear to be equally effective for isomorphic transfer. However, there is at least one finding that suggests a slight edge to materials-based plus teacher support condition.
3. There is evidence for non-isomorphic transfer.
4. There does not appear to be differences in the effectiveness of the transfer supports for non-isomorphic transfer.
5. The evidence for "Preparation for Future Learning" (PFL) is inconclusive.
6. There is clear persistence of learning during the course of the year.

Taken together, the evidence suggests that learning of causal forms can transfer and can impact later learning. This was so both in the case of isomorphic and non-isomorphic transfer, though the case here for isomorphic transfer is stronger. The evidence around "Preparation for Future Learning" is mixed and somewhat inconclusive. Further, there is evidence of persistence of effects of the causal learning for the course of the school year and up to two years later.

We conclude that with the right kinds of shepherding, transfer of causal forms can be achieved. The current analysis suggests that materials-based interventions can be just as effective as more intensive teacher-supported ones. This is important given the greater likelihood of the first occurring in schools in contrast to the second. Of course, it is difficult to imagine that teacher support in the hands of a very capable teacher would not be more effective than mere materials-based support. The analysis here hinged on the effectiveness of the particular interventions and ability of the teachers and researchers to carry it out. As we learn more about how causal teaching can become a part of the lives of classrooms, even more effective materials-based and teacher support can be developed. However, it is important to note that materials-based intervention can be effective and can serve as a high leverage curriculum component in helping students learn to deeply understand scientifically accepted explanations. These transfer findings taken together demonstrate that the teaching of causal concepts can effectively reach beyond the immediate contexts in which it is taught.

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 as diSessa (1993) has written about, that affect transfer. P-prims (or phenomenological primitives) are small knowledge structures that people use to describe a system's behavior. Though not necessarily generalizable beyond the particular contexts that elicit them, these schemata come into play as ready explanations or components of explanations. They are often considered to be self-explanatory and to need no justification. For instance, we have seen students struggle with applying a relational model to situations involving air pressure when they have a strong competing "force as a mover" (diSessa, 1993) notion as in explanations of the wind or hurricanes (Ritscher, Lincoln, & Grotzer, 2003). 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 A: 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 to 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; g/cm3 [grams per cubic centimeter] or 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 A: Lesson Descriptions for Pressure Unit

Lesson 1: What is pressure? Students in both groups were introduced to the concept of pressure in contrast to the idea of force. They were encouraged to consider force and pressure as two related, yet distinct concepts. Activities such as "The Bed of Nails Demonstration" helped illustrate the relationship between force and pressure. They were taught that pressure and area are inversely proportional.

Lesson 2: Does air exert pressure? Students were taught that air exerts pressure, but that because we are constantly surrounded by air, we often don't notice air pressure. Students lifted an inverted lab table by blowing air into a number of balloons set up between two tables. They also observed what happens when you take the cap off a bottle full of water that has holes in it. Without the additional air pressure, the liquid will stay in the bottle, but when you unscrew the cap, the air pressure on the liquid causes it to squirt out the side. Students in the Causal Groups discussed the difficulty of noticing non-obvious causes.

Students' attention in the causal group was drawn to the non-obvious nature of pressure. They were taught that pressure exists in all situations at all times. We sometimes forget to consider pressure because the effects of pressure are such a common aspect of our lives. They had explicit conversations about this phenomenon as a result of our trouble understanding non-obvious causes or effects and that a change in pressure can make its non-obvious effects obvious. Teachers demonstrated this through a RECAST activity where a balloon is inflated by removing the air in a sealed bell jar.

Lessons 3 and 4: How does air pressure affect our daily lives? Students considered the role of air pressure involved in everyday phenomena. They were presented with a list of questions (such as "Why are airport runways longer in Denver than in San Francisco?" Or "Why do your ears pop when taking off in a plane?"). Students were given time to discuss and brainstorm ideas with their peers. The questions were hung up in the room and addressed throughout the rest of the unit. In this lesson, no final answer was established to any of the questions. At the end of the unit, however, the questions were revisited and addressed explicitly. This enabled the teacher as well as the students to see how their ideas have shifted as a result of the unit.

Students in the Causal Group continued to explore the importance of considering non-obvious causes in air pressure related phenomena. Specifically, they discuss and model their ideas about the how the balloon inflated inside the bell jar in the previous lesson, while considering non-obvious or hidden causes. Students in the Basic Group discussed the same questions at the Causal Students discussed in Lesson 3 pertaining to examples of air pressure found in everyday life. Like the Causal Group, the students were encouraged to think freely about the questions and to model and discuss their ideas without coming to any firm conclusions as a class at this point.

Lesson 5: What is the relationship between force and pressure? Students were given opportunities to practice calculating pressure by dividing the force by the area upon which the force is applied. They were also taught that solid pressure is measured in Pascals. They continued to explore the relationship between force and pressure by engaging in more activities illustrating this concept.

Lessons 6 and 7: What are some useful models for thinking about air pressure? Students were asked to develop models to explain what as going on in a couple of different air pressure-related phenomena. For instance, students tried to explain the idea that air exerts pressure and to consider what this means for everyday situations. Students in the Causal Group also developed and compared models. They were introduced to models illustrating relational causality and the idea that when the pressure within an object and the outside pressure are unequal or unbalanced, we are more likely to notice the effects of pressure. Second, students learned that using relational causality could help them understand how differences in pressure can cause effects, such as areas of higher pressure moving towards areas of lower pressure until equilibrium is achieved.

Students in the Causal Group continued their explicit conversations about how relational causality can help them think about pressure differentials. They were given hand-outs about thinking about relational causality versus linear causality and the teacher engaged students in explicit discussion on this distinction.

Students in the Causal Group were encouraged to reason about a puzzling phenomenon for which using a relational model helps to clarify what was going on. It reinforced the importance of analyzing pressure phenomena relationally rather than using linear models or token agents. Students engaged in the RECAST activity: The Three Flasks in this lesson.

Lessons 8 and 9: What is Boyle's Law? Students in the Basic Group learned that although the relationship between force and surface area defines pressure, volume and temperature affects pressure. The lesson focused on Boyle's Law, which states that at constant temperature, the pressure times the volume of an enclosed gas remains constant; when one increases, the other decreases to maintain equilibrium. Students analyzed the relationship between volume and pressure by experimenting with putting their thumbs over the end of a syringe. They also used the software, Stark Design's Molecular Dynamics, to help illustrate this concept.

Students in the Causal Group applied a relational causal model to understanding Boyle's Law, which focuses on how the pressure and volume within a closed system are related. They took it one step further and extend it beyond a closed system to see how Boyle's Law affected outside pressure as well. Teachers used plastic syringes and the computer software, *Stark Design's Molecular Dynamics*, to help students understand this concept.

Lessons 10 and 11: What is Charles' Law? Students in the Basic Group developed an understanding of Charles Law, that is, if the temperature of a fluid increases, the volume also increases and vice versa. They did experiments involving heating a flask with a balloon attached to the top.

Students in the Causal Group apply the relational causal model of pressure to understand Charles Law, which focuses on how the volume and temperature within a closed system are related (at constant pressure). However we will take it one step further and extend it beyond the closed system to see how the outside pressure may affect the overall system. Like the Basic Group, they experiment with heating a flask with a balloon attached at the end. They also used *Stark Design's Molecular Dynamics*. The students were asked to consider a system in which the balloon gets pushed into the flask as it cools. Using a relational model explains the event, but only if one uses keen observation skills and notices the moisture formed on the inside of the flask. The cause was initially non-obvious (water vapor) but became obvious as the moisture forms during cooling. However, it is not intuitive to form a relationship between the moisture (resulting in lower pressure inside the flask) and the end result (the balloon pushed into the flask from the higher pressure outside) so students needed help coming to this understanding.

Lesson 12: What does air pressure have to do with lift?: Bernoulli's Principle Students in the Basic Group learned that lift is due to pressure. They also learned that Bernoulli's principle says that fast-moving air exerts less pressure than slow-moving air. Students in the Causal Group learned that a relational model of pressure can be used to explain lift and Bernoulli's Principle.

Lesson 13: How does pressure affect our lives?: Revisited Students in both groups went back to the questions presented earlier in the unit and discussed how their thinking had changed.

Appendix A: Lesson Descriptions for Heat and Temperature Unit

Lesson 1: What happens when matter changes state?: Collecting data on the phase changes of water Students in both groups discussed their ideas about how matter changes state (by focusing on the phase changes of water) and collected data using Pasco temperature probes to analyze during the subsequent lessons. Students were taught that when energy is added to or removed from matter, its temperature *or* its state will change. In order for objects to change state, from solids into liquids and from liquids into gases, they must *absorb* energy.

Lesson 2: What happens when matter changes state?: Analyzing data on the phase changes of water Students in both groups analyzed the data that students collected in the first lesson to consider what it reveals about the relationship between heat energy and phase change. Students created graphs to look for trends in their data. Like the first lesson, students were taught that when energy is added to or removed from matter, its temperature *or* its state will change. Furthermore, in order for objects to change state, from solids into liquids and from liquids into gases, they must *absorb* energy.

Lesson 3: What happens when matter changes state?: Addressing counterintuitive ideas In both groups, teachers addressed some key misconceptions that students often hold around the idea of phase change. Students were engaged in activities that helped them understand that evaporation is a cooling process in which the change in state goes from a liquid to a gas at the surface of the liquid. They also learned the following phase change concepts: boiling is the change in state from a liquid to a gas beneath the surface of the liquid; condensation is the change in state from a gas into a liquid; freezing is the change in state from a liquid to a solid; melting is the change in state from a solid to a liquid; and finally, as objects change from gases to liquids to solids, they release energy.

Lesson 4: Heat and temperature: Is there a difference? Students in both groups were taught that temperature is not the same thing as heat by showing them a demonstration in which different types of liquid were heated, brought to a boil and melted an ice cube.

Lesson 5: Heat and temperature: What is temperature? For both groups, students in this lesson were introduced to the idea that temperature measures the movement of molecules--the average kinetic energy of the atoms that make up matter. They were also given opportunities to take measurements using different scales (i.e. in Fahrenheit, Celsius, and Kelvin scale).

Lesson 6: Heat and temperature: What is heat? The students in both groups were introduced to the idea that heat is energy that “flows” from one object to another (from high energy to low energy) because of a temperature differential. Students in the Causal Group discussed heat flow by thinking analyzing patterns of causality. They considered which the patterns are unidirectional or mutual. Students in the Basic Groups also discussed the pattern of heat transfer, but without the discussion on causality. Both groups analyzed the flow of heat and created models of what happens when you place an ice cube in your hand.

Lesson 7: Thermal energy: What is thermal energy and thermal equilibrium? Students in both groups were introduced to the concept that heat energy flows until thermal equilibrium is reached. Both groups explicitly discussed the differences between potential, kinetic, and thermal energy.

Lesson 8: Thermal energy: How can we use specific heat to identify an unknown metal? Students in both groups explored the idea that heat lost by a material equals the heat gained another material inside a closed system (conservation of heat energy). Also, they were taught that an object's thermal energy depends upon its mass, specific heat, and temperature. The specific heat of an object is the amount of heat energy required to raise the temperature of a unit of mass of a material by one degree Celsius. The specific heat of water is much greater than the specific heat of metals and most other materials. In both groups, students did a calorimetry lab, heating and measuring different unknown metals to try to identify them by their specific heats.

Lesson 9: Transfer of heat: What is conduction? In both groups, students were introduced to the concept of conduction—the transfer of heat through matter by direct contact of the atoms. Both groups discussed that solids are the best heat conductors because their atoms are closely packed together and that solids that conduct heat well are called conductors; those that do not are called insulators. Both groups also discussed how faster moving particles bump slower moving ones and energy is transferred until equilibrium is reached. Students in the Causal Group, however, explored these ideas through the lens of domino causality. They also discussed how conduction can be difficult to understand because it is an effect of non-obvious cause(s) on the atomic level.

Lessons 10 and 11: Transfer of heat: What is convection? Students in both groups were introduced to the concept of conduction—the transfer of heat in liquids through the movement of currents. Students learned that convection is the process of heat transfer in fluids through the movement of currents and that it is an application of Archimedes Principle, as warmer fluids are forced (buoyed) upward by the colder, denser surrounding fluid. Students in the Causal Group discussed convection as 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. Students in both groups did experiments of heating food coloring in a beaker full of water to watch the convection currents.

Lesson 12: Transfer of heat: What is radiation? Student in both groups were introduced to the concept of radiation—the transfer of heat in the form of electromagnetic waves. Heat energy that is transferred by radiation, in the form of electromagnetic waves, is called radiant energy. An object that is a good absorber of radiant energy is a poor reflector of it. An object that is a good absorber of radiant energy is a good emitter of it. Students in the Causal Group discussed the idea that radiation follows a multi-linear radiating pattern. In both groups, students experimented with different colored paper wrapped about test tubes to examine the differences between reflection and absorption.

Appendix B: 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, **or** mentions pressure (**or** any other non-obvious variable) as a token explanation	…acknowledges a difference or change in pressure but does not elaborate, **or** 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."

<u>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</u>

"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."

<u>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</u>

"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."

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

"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]

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

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

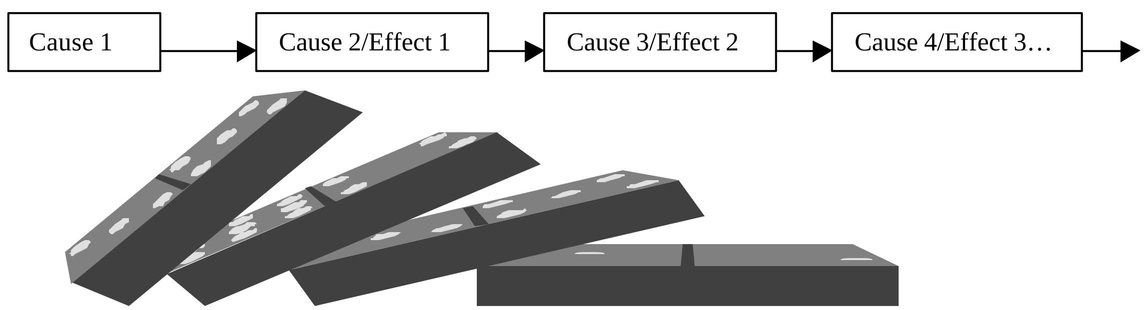
<u>Level 5: The student implicitly or explicitly acknowledges the pressure differential/ equation and interaction</u>

"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."

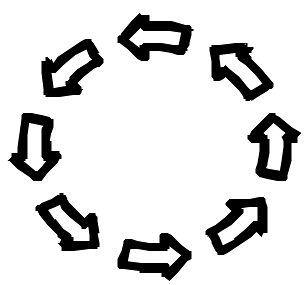
"In the mountains there is less pressure than at the beach. When she bought the balloon in the mountains, there was less pressure on the gas inside, so the balloon can expand all the way. When she drove down to her beach house, the pressure outside on the balloon increased, and the air inside the balloon 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."

Appendix C: Examples of Types of Causality

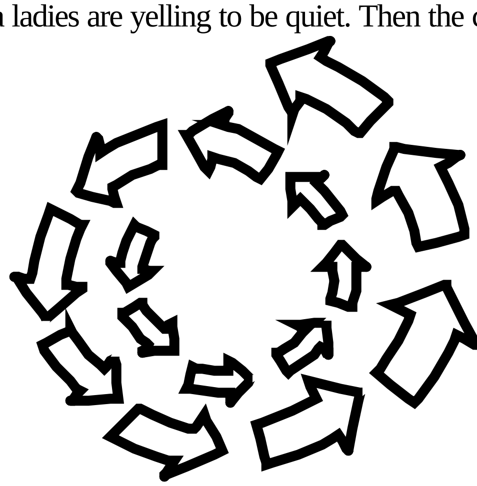
1. **Domino causality:** Each thing that happens then causes something else to happen. Things don't just stop with the one effect. It works just like a branch of dominoes where one hits the next and then that effect causes the next one to fall and so on. So for example if one person comes to school sick, they might get the teacher sick, then everyone has a sub, then everyone learns a little less science and on the other branch, their friend might get sick, might miss a sports event that he or she was looking forward to and so on…



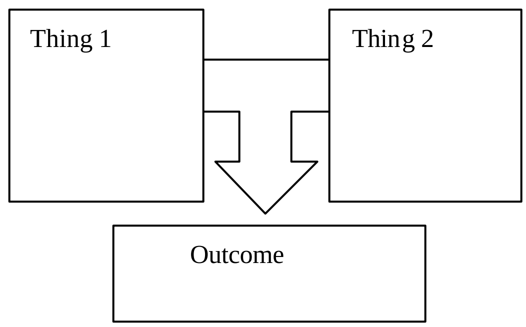
2. **Cyclic causality:** It works like a circle so that one thing happens that, in turn, makes the first thing happen (which, in turn, makes the first thing happen again and so on.) An example is the water cycle, where it rains, then water evaporates in the atmosphere, where it condenses into clouds and causes it to rain again.



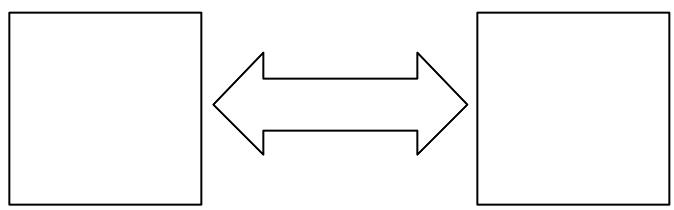
3. **Escalating causality:** It is a form of cyclic causality, each time it goes around, the level increases. For example, in the cafeteria, the person next to you talks a little louder so that he/she can be heard over you, then you talk a little louder to be heard over them, then they talk even a little louder to be heard over you, and so on until the cafeteria ladies are yelling to be quiet. Then the cycle starts up again.



4. **Relational causality**: A relationship between two things causes the outcome. For instance you can't be an older sister or brother without having a sibling whose age is less than yours. It is the relationship between your ages that makes you older or younger than someone else.



5. **Mutual causality:** Two things affect each other (not necessarily in the same way). One event typically has an impact on both. The event might help both people (mutually beneficial) or it might help one at the expense of another (a thief stealing, for example).



Appendix D: Mapping Causal Forms

Name ________________________________ Block __________ Date ________________

Mapping Out Relational Causality

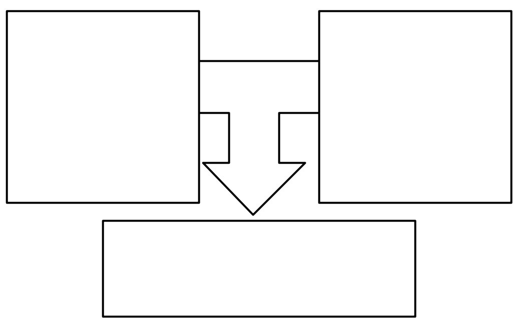
An object or a liquid can sink or float in another liquid, but neither liquid nor object alone is the "cause" of sinking and floating. It is the relationship between the two densities that "causes" sinking and floating. You can make comparisons about the relationship. For example, you can say that one is more dense and one is less dense, but it only makes sense in terms of the relationship, in comparison to each another.

Let's map out how each is a relational causality:

In relational causality…

1. …a relationship between two things causes something to happen. (So it is more than just having two things, there needs to be a relationship between them.)

a. In the top two boxes, write what the two things are.
b. In the middle of the arrow, tell what the relationship is.
c. In the bottom box, tell what the effect is.



2. …comparisons or differences between the two things are responsible for something happening or being so.

What comparison is responsible for the outcome in the role of density in sinking and floating?

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