Understandings of Consequence in a Complex and Uncertain World[1]

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Three Examples (and Plenty More Where Those Came From…)

> The Biofuel Plan will lessen our dependence on foreign oil, so it was argued. It also appears to be increasing food prices here and abroad. Combined with growing demand for food from China and India and the collapse of grain harvests due to drought, using more corn and more cropland to grow corn for ethanol has increased prices for other grains and those other foods based on grains such as beef, milk and eggs. Food riots have ensued in Haiti, Somalia, Bangladesh and Mozambique.

> The disaster at Chernobyl was due to human error, specifically an inability to manage the dynamic processes of the system as opposed to the state of the system at a given moment. As written about by Dorner, [2] during a safety test, engineers planned to take the reactor down to 25% of its operating capacity. In manually controlling the system, the operator overshot in response to the reactor's self-dampening behavior. When the system dropped to 1% of capacity, the operator began to focus on correcting the current situation, rather than the systemic processes in play, acting in ways that increased the instability of the system and setting in motion the catastrophic events of that day.

> In the early 1950s, the Dayak people in Borneo suffered from malaria. The World Health Organization sprayed large amounts of DDT to kill the mosquitoes that carried the malaria. The mosquitoes died and the malaria declined. But that's not all that happened. The roofs of people's houses began to fall down on their heads. The DDT was also killing a parasitic wasp that had previously controlled thatch-eating caterpillars. Geckoes ate the DDT poisoned insects and cats are the geckoes. The cats died and rats flourished resulting in outbreaks of Sylvatic plague and Typhus. To cope with these problems, which it had itself created, the World Health Organization parachuted cats into Borneo.

As the examples above illustrate, complex causality is part of our world. Causal complexity comes in many forms. It includes non-linear patterns such as mutual, relational, cyclic and escalating causalities. It can be complicated in how it plays out in space and time, involving time delays, spatial gaps, and near simultaneity between causes and effects (such as in a set of gears turning.) It involves intentional as well as non-intentional causes and centralized as well as distributed ones.

In our daily lives, we have many opportunities to analyze the nature of complex causality and to apply the principles to new instances. However, this is not typically what happens. A growing body of research offers insights into how people handle causal complexity.[3] Similar to the reductive biases that Feltovich, Spiro, and Coulson[4] identified in how people handle other forms of complexity, people often use simplified causal forms that are in tension with the inherent complexity of the problem space. Table 1 summarizes these tendencies. There is substantial support for these tendencies in the research literature.[5] If the world were simple, this might not matter but as the examples illustrate, simplifying a complex world can lead to misconceptions and mishaps!

How people reason about risk, events such as 9/11, the possibility of pandemics such as SARS, the spread of insect borne disease such as West Nile Virus, diseases with extended onset such as Mad Cow Disease, and Hurricane Katrina hinges upon how we allocate our attention and this, too, is impacted by the types of causal complexity involved. Compare poor eating habits with sitting near a bees' nest. For most people, bee stings are not life threatening, but the impact is immediate and obvious and upon discovering a bee's nest nearby, most people would go through the trouble to move. Heart disease is life threatening, but not immediate or obvious and behavioral change is a lot harder to come by. Similarly, an intentional cause as in terrorism is harder to ignore than a non-intentional cause as is the case with global warming.

Can we learn to recognize default patterns and to shift our thinking? There are plenty of examples of learning the hard way, such as cats on parachutes. Often it takes such a focusing event to garner our attention. This in and of itself is a problematic approach to a complex world. Lake Nyos is a lake in Cameroon about 200 miles northwest of the capital of Yaounde. In 1986, gases from the lake escaped into the atmosphere displacing the oxygen and nearly 1800 people died. Relational causality describes the pattern of the tragedy. Gases with different densities form layers in the atmosphere as denser gases sink on less dense gases. Lake Nyos is located in a part of Cameroon that is volcanically active. Carbon dioxide gas from this underground volcanic activity built up at the bottom of Lake Nyos over time, like the dissolved carbon dioxide in a can of soda. Two other facts are important. Colder water has the potential to support more dissolved gas than warmer water and carbon dioxide is denser than oxygen. Prior to the event, the lake water appears to have had stable stratification with only partial mixing when the gases were released. Whether there was a particular trigger, the lake was saturated, and/or the warm August weather contributed or a number of factors interacted to result in the gas release is unclear. But the relationship between the density of the two gases resulted in nearly 1800 suffocating in their sleep. However, the whole story of what happened at Lake Nyos involves telling a related story—the one about how people attended to events at the lake prior to the disaster of 1986 and how they attend differently now. In studying the event that caught our attention, scientists realized that the whole scenario could play out again—that carbon dioxide was again collecting in the lake. Therefore, they built an extraordinary fountain in the lake that is designed to disperse the gas over time—in essence managing the state of the lake rather than focusing on events as they happen. While the level of carbon dioxide continues to be a concern, managing the gas levels may well prevent another catastrophic event. Focusing events can gain our attention, but managing the causality, in this case, involves attending to the steady state.

Buttons, Puddles, and Playground Politics: Causality within Reach

Can we teach the next generation to do a better job reasoning about causal complexity? Causality may sound like an esoteric concept, but children think about it everyday implicitly, if not explicitly—building fundamental, structural knowledge that they'll draw upon over the course of their lives. Consider the following examples.

> A toddler pushes every button and light switch that he can find. His mother thinks that he is just trying to push her buttons. He is actually finding out that causes do not have to physically touch their effects—that causes can act at a distance. Someday, he may consider causal action at a distance as he analyzes the impact of nuclear waste disposal in one area on an area upwind.
>
> A kindergartner jumps over puddles on the playground. Misjudging one, she falls in with a splash. Cold and wet, she gets her dry clothes from her cubby. In warm dry clothes, she resumes jumping over puddles. When asked whether she is making a good choice, she responds with certainty, "I am not going to fall in again." She is learning to think about chance events and to balance those against her growing skills. Someday she may use this knowledge when judging whether to perform a delicate surgery.

> A fifth grader watches two friends get in an argument. The conversation spirals out of control as each side escalates in their anger—saying things that they would never have said outside the context of the conflict. Remembering a recent lesson, he runs in to tell his teacher, "Ms. Ryan, Ms. Ryan, we have escalating causality and need a cool down." Someday he may use this knowledge to help manage conflict between factions in a war torn country.

These examples underscore what an extensive developmental literature substantiates (See Grotzer, 2004 for an in-depth review.) From fairly young ages, children reveal developing competencies related to complex causal forms. But we know that developing an extensive and articulate causal repertoire it isn't going to happen without effortful attention throughout the curriculum.

Getting Beyond Simple: A Causal Curriculum for Today and Tomorrow

What does it mean to teach about complex causality? What would such a curriculum entail and how effective would it be? Does the teaching of causal patterns really work and even if it does, how can teachers justify spending time on it when they are accountable to the standards? For the past ten years, with generous funding from the National Science Foundation, we have been researching and working extensively in pre-K-12 classrooms to develop ways of teaching the causal concepts in Table 1. A critical question that we had at the outset of our work was whether it was possible to integrate the teaching of causality into the curriculum to teach for the future and still meet the current standards. Our work in classrooms suggests that it is not an either or proposition. We saw significant and substantive gains in causal understanding and in curriculum content in the performance of students in classes where we taught the causal concepts in the context of the curriculum. These gains showed up on the standardized tests that students took as well as on supplementary tests that we gave to probe for deeper understanding. Equally encouraging to us were the stories that the teachers and principals reported of students who returned from high school or college to talk about what a difference it had made to them. They talked about "learning to really think" and finding "those causal patterns everywhere I looked, even in the supermarket!" When we systematically interviewed the students with whom we had worked in earlier years, across the board, they had held onto the science gains that they had made and many of them reported similar life stories about the impact of the work.

Adding anything to the curriculum is hard. Yet, these concepts are already implicit to understanding the curriculum that we have. Pulling them out to explicitly focus on them enhances the learning students already have to do and better prepares them for the future. We have the opportunity within the context of the current curriculum to help students learn to reframe their causal thinking. By extending their causal repertoire, we can empower them to understand their world better, choose more informed actions, and to be critical consumers of proposed policy.

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[1]This work is excerpted from: Grotzer, T.A. (in prep). *Understandings of consequence: Educating students for the world of today and tomorrow*. Rowman & Littlefield: Lanham, MD. Please do not cite or quote without permission.

[2]Dorner, 1989.

[3]Research on how people handle causal complexity: e.g. Chi, 2000; Grotzer, 2003; 2004; 2007; Hmelo-Silver, Pfeffer, & Malhotra, 2003; Perkins & Grotzer, 2000; Wilensky & Resnick, 1999).

[4]Feltovich, Spiro, and Coulson (1993)

[5]Research Support for Tendencies (e.g. Ferrari & Chi, 2000; Grotzer, 2000; 2004; Grotzer & Basca, 2003; Houghton, Record, Grotzer, & Bell, 2000; Perkins & Grotzer, 2000; Resnick, 1996; Wilensky & Resnick, 1999).

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Table 1. Concepts for a Causal Curriculum:
Teaching Students How To Handle Complexity

Simplistic Framing:	How does it work?	Reframing for Complexity:	How does it work?	How we tend to get stuck…
Simple Linear (“This Makes That Happen” Causality)	One thing makes another thing happen.	Extended or Non-linear (Domino, Cyclic, Mutual, or Relational Causality)	Causal patterns can be extended or non-linear. They can include indirect or bi-directional effects.	We often adopt simple story-like notions where one thing happens to cause something else. We miss patterns that are like dominos, cyclic as in a feedback loop, mutual as in symbiotic relationships or relational where a relationship between two variables causes an outcome.
Event-based (“What Happened?” Causality)	Something has to happen in order for us to think about causality.	Steady States and Processes (“What’s Going On?” Causality)	Systems in balance and processes entail causality even if nothing is happening at the moment.	Unless something is happening, we don’t think about the causal relationships in play. A bridge shouldn’t have to fall down in order for us to realize what was causing it to stay up. Similarly a government shouldn’t have to collapse for us to realize what was working. (Factors such as accumulation or triggering events can rapidly transform a situation from “What’s going on to “what happened?”
Sequential (“Step by Step” Causality)	Causes always come before effects in a step by step pattern.	Simultaneous (“All at Once” Causality)	Causes and effects can co-occur in time and still have a causal relationship.	We expect that causes have to occur before effects in our causal explanations even when it doesn’t fit what is happening. Gears all turn at once even though one causes another to turn.
Obvious Variables or Mechanisms (“Easy to Notice Causes and Effects”)	Some causes (and some effects) can be directly perceived.	Non-Obvious Variables or Mechanisms (“Hard to Notice Causes and Effects”)	Some causes (and some effects) are non-obvious because they are microscopic, imperceptible, or inferred.	We focus on obvious causes instead of non-obvious ones. Students are more likely to report worms as decomposers than microbes. We don’t think about air pressure as the cause of ear aches on planes unless we have been told to. We do reason about inferred causes such as intentions in social situations, but we reason in more complex ways about ourselves than others.

Active or Intentional Agents ("Who Did It?" Causality)	Many cause and effect relationships involve an actor who intends a certain outcome. Many actions have a purpose or intent.	Passive or Unintentional Agents ("No One Did It" Causality)	Some causal relationships don't involve action or intentionality. Or actors and their intentions may not correspond with effects at another level of problem analysis.	We tend to look for whom or what made something happen. We assume active and intentional agents. Yet, seatbelts, a passive restraint system, cause us to stay in the car when it stops without actively doing anything. Electrons are active and protons are passive, yet neither is intentional. When we drive our cars, we intend to get to where we are going but we don't intend to contribute to global warming.
Deterministic ("It Always Works" Causality)	An effect always follows a given cause.	Probabilistic ("It Sometimes Works" Causality)	An effect sometimes follows a given cause.	In part, we judge whether a causal relationship exists by how reliably the effect follows the cause (in a kind of Bayesian analysis.) Over-reliance on correlation gets us into trouble. We assume causality where only correlation exists (unless we also search for mechanisms). We also tend to use lack of reliability to discount the relationship. One might think, "I did it before and I didn't get sick, so I'm not going to get sick now" instead of "Even if I didn't get sick before, I can still get sick now."
Spatially and Temporally Close ("Local Causes and Effects" or "Immediate Causes and Effects")	Causes and effects physically touch each other or are close to each other in space and time.	Spatially and Temporally Distant or Delayed ("Distant Causes and Effects" or "Slow" or "Delayed Causes and Effects")	Causes can act at a distance and there can be delays between causes and effects. Sometimes effects need to accumulate to a certain level to be noticeable or they must reach a trigger point before which there is no effect.	We often limit our search for causes and effects to those that are close together in space and time missing more distant causes or parts of causes. Or we miss the distant effects of an event that we are aware of. We misunderstand events in the Middle East because we view them in too brief a time span. We think that satellites have a force within that drives them instead of an orbit resulting from a combination of gravity on Earth and continued forward motion. Teenagers think, "I can't see any bad effects of getting a suntan right now" instead of "The hurtful effects of getting a suntan accumulate and show up after a long delay between cause and effect."
Centralized ("Someone's in Charge" Causality)	A central figure or leader causes (and typically intends) the outcome.	Decentralized ("Nobody's and Everybody's Fault" Causality)	Individuals interacting give rise to an emergent effect where the intent of the individuals often has nothing to do with the higher level outcome.	We tend to focus on centralized authority or causes and don't attend enough to the power of distributed causality. So we think that government institutions and leaders rather than our individual, daily civilized actions give rise to a civilization. Or we wait for our leaders to enact legislation to combat global warming rather than changing our individual actions to contribute to the emergent solution.

Six Causal Patterns

Linear Causality

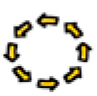
- Cause precedes effect; sequential pattern
- Direct link between cause and effect
- Has a clear beginning and a clear end
- Effect can be traced back to one cause
- One cause and one effect; additional causes or effects turn this pattern into domino causality

Can you think of an example?

Domino Causality

- Sequential unfolding of effects over time
- An extended linear pattern that results in direct and indirect effects
- Typically has a clear beginning and a clear ending
- Can be branching where there is more than one effect of a cause (and these may go on to have multiple effects and so on.)
- Branching forms can be traced back to “stem” causes
- Anticipating outcomes involves deciding how far to trace effects. Short-sightedness can lead to unintended effects

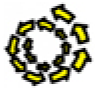
Can you think of an example?



Cyclic Causality

- One thing impacts another which in turn impacts the first thing (or alternatively impacts something else which then impacts ma impact something else and so on, but eventually impacts the first thing)
- Involves a repeating pattern
- Involves feedback loops
- May be sequential or may be simultaneous
- Typically no clear beginning or ending (Sometimes you can look back in time to a beginning but often that results in the classic which came first, the chicken or the egg problem.)

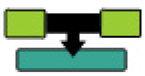
Can you think of an example?



SPIRALING CAUSALITY

- One thing impacts another which in turn impacts the first thing (or alternatively impacts something else which then impacts ma impact something else and so on, but eventually impacts the first thing) with amplification or de-amplification of effects
- Involves feedback loops
- It is sequential as each event is a reaction to the one before it
- Often a clear beginning and ending
- It is difficult to anticipate outcomes of later feedback loops during earlier feedback loops

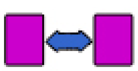
Can you think of an example?



RELATIONAL CAUSALITY

- Two things in relation to each other cause an outcome
- It often involves two variables in comparison to each other
- There may be a relationship of balance, equivalence, similarity or there may be a relationship of difference
- If one thing changes, so does the relationship, therefore so does the outcome
- If two things change but keep the same relationship, the outcome doesn't change

Can you think of an example?



MUTUAL CAUSALITY

- Two things impact each other
- The impact can be positive for both, negative for both, or positive for one and negative for the other
- The causes and effects are often simultaneous, but can be sequential
- May be event-based or may be a relationship over time (such as the moss and the algae in lichen

Can you think of an example?

Putting Everyday Science Within Reach

By Tina A. Grotzer

PREVIEW

Students tend to make fundamental assumptions that make it difficult to learn in science.

Helping students understand the structure of knowledge improves their achievement.

Unpacking thinking has the most dramatic effect for low-achieving students.

Let's be honest. When you saw that the title of this article was related to science, did you gloss over it and think, "I'll pass that one along to the science faculty" or did you think, "I'll dive in and try to make sense of it"? If your response was the first one, you are not alone. The tendency to view science as specialized and inaccessible is common. As a result, many people don't persevere in trying to understand it. Although administrators give it a nod in terms of being important, they often see it as something for students who have certain kinds of intelligence and, unlike reading, accept less-than-deep understanding of science by everyone else. Although science does involve some unfamiliar patterns of thinking, these are patterns everyone can learn—to their own benefit and that of their students.

What Is Specialized?

When educators talk about thinking like a scientist, they typically refer to process or inquiry skills. These skills are represented in the national standards and include systematically controlling for and testing variables, formulating questions, and interpreting data. These are important ways of finding out and knowing in science.

However, there is another form of thinking in science that is not yet represented in the standards but clearly affects students' achievement. Referred to as *structural knowledge* (e.g., Grotzer, 2002; Jonassen, Beissner, & Yacci, 1993), it deals with 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. Recent research shows that scientists often make different assumptions than the rest of us (e.g., Ferrari & Chi, 1998; Hmelo-Silver, Pfeffer, & Malhotra, 2003) and that helping students understand what those assumptions are deepens their understanding and improves their achievement (e.g., Grotzer & Basca, 2003; Grotzer & Sudbury, 2000).

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The Science and Complexity of Everyday Life

But first, why bother? What's wrong with leaving science to the scientists and focusing on ways of thinking that are inherently more familiar? One reason is that science can't be relegated. Students deal with aspects of science everyday, just not particularly well. They erroneously think that steam isn't as hot as boiling water and that cars are safe in thunderstorms because cars have rubber tires, and they then extend the concept to their sneakers, and so on.

A second reason has to do with where complexity is found. One could argue that some forms of science should be relegated to scientists, such as chaos theory or quantum mechanics. However, everyday science involves some of the same sources of complexity. For example, forms of complex causality are involved in the science of what happens when a person drinks from a straw, why a person sometimes gets sick when around others, and why a person can tolerate a certain level of exposure to toxins but not more. Further, these forms of complex causality, although important to understanding science, are also present in other areas of life.

Consider: Students are talking in the cafeteria. They all want to be heard by the student beside them, so each student speaks a little louder to be heard over the others. This results in an escalating causal pattern in which the noise level gets louder and louder. On top of that, none of them feel responsible for the increased volume because the agency is distributed. It involves a decentralized causality where the cause is spread across many students. Such causal patterns are also involved in acid rain, global warming, and the growth of slime molds. But these patterns are also common in social events, including interactions in the monthly faculty meeting, grassroots campaigns, traffic jams, and the Cold War. Understanding them is powerful in science and in the science of everyday life.

Default Thinking Patterns

If students aren't reasoning like scientists, how are they reasoning? Over the past 25 years, researchers have been investigating students' ideas in science. A wealth of research shows that students come to school with naive but firmly rooted theories of how the world works (e.g., Driver, Guesne, & Tiberghien, 1985). Gardner reviewed this

Activities That Teach Expert Causal Thinking Patterns

Imagine two classes that are studying density by experimenting with things that sink and float, a common activity in density units. In the first class, students list which objects sank, which floated, and which suspended and attempt to draw conclusions from their observations. "The heavy things sink and the light things float," they observe. Their teacher attempts to push the students' thinking by having them compare objects that control for certain variables—a large and small piece of the same kind of wood, for example. A lot of good things are happening in the classroom. Students are engaged, are learning epistemological skills, such as the nature of knowing and finding out in science, and are trying to answer a question related to an important and fundamental concept.

In the second class, students are also trying to figure out about sinking and floating. They think that they understand why a large piece of candle in one beaker sinks but a small piece in another beaker floats. "It definitely has to do with the size and weight," they agree. The teacher asks them to swap the pieces of candle. Much to their amazement, the large candle floats and the small candle sinks. Their attention is pushed to the liquid and they begin analyzing what is going on in terms of the relationship of the candle to the liquid. These students are also engaged, are learning the epistemology of science, and so on. However, they are also learning something else.

The activity in the second class was carefully designed to reveal the causal structure involved in sinking and floating. Its design is based on the fact that students often use simple linear explanations (the weight of the object makes it sink) and miss nonobvious, intensive, or ambient variables (such as density). The activity reveals that a linear causal explanation is inadequate and that one needs to consider the relationship between the object and the liquid in a form of relational causality. It is called a *RECAST activity* because it is designed to Reveal the underlying Causal Structure (Grotzer, 2002). *RECAST* activities illustrate, through results that are at odds with students' expectations, that the structure of the causality involved is different than students expected, and they offer insights into the nature of that causality.

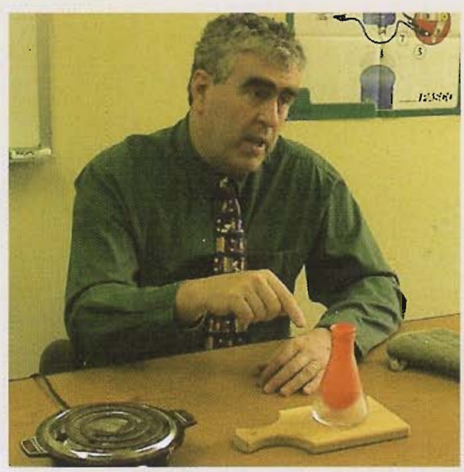


PHOTO COURTESY OF AUTHOR

Everyday Science Questions

What happens when I drink from a straw? What makes the juice rise in the straw?

Why do my bicycle tires look flat in the winter but not in the summer when no air has been added?

Why do planes fly?

Why do some things sink and some things float in the same liquid?

Why do things break down into soil even when no worms are around?

Why do all the lights in a school hallway come on at the same time when you flip the switch?

Why does bread get moldy?

Why do satellites circle the earth with no driver and no fuel source?

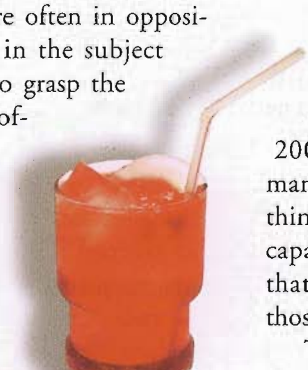
Why do I sometimes get sick if I am around a sick person and sometimes not?

How do the gears on a bicycle work?

How does the cream poured into coffee spread out even if it isn't stirred?

research in his 1991 book, *The Unschooled Mind.* Students develop theories over time based on their own observations, so the theories make a lot of sense to them. It can be overwhelming for teachers to try to address a classroom full of naive, individualized theories. However, current research suggests that although some of these theories are idiosyncratic, others stem from a set of common default assumptions and are shared by many students.

When coming up with explanations, students reveal "a reductive bias" (Feltovich, Spiro, & Coulson, 1993). They tend to make a set of nine simplifying assumptions (Perkins & Grotzer, 2000). 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 storylike: First this happened, then it made that happen, and so on. These explanations have a domino-like quality to them. However, much 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. Many teachers recognize that such difficulties exist for the science of complexity but do not realize that this is also the case for everyday science. Students apply simplifying assumptions and end up distorting the concepts.

Students find it especially hard to depart from their simpler models when their perceptions are highly visceral, as in lightning or hurricanes. Despite what they have learned about static electricity, students argue that lightning has to be linear because it "comes down from the sky." This makes it unlikely that they will notice phenomena on the ground to suggest lightning is about to strike around them—such as their hair starting to stand up—observations that can be life saving. Further, students often assume that there is a deterministic relationship between cause and effect—effects always follow causes. This can get them in trouble and lead to risky behaviors when they also assume the inverse, "I did it last time and I didn't get sick, so I won't get sick this time."

Expert Patterns of Thinking

The scientific patterns may be unfamiliar, but they are entirely learnable. Research clearly shows that students can learn forms of thinking with explicit attention for doing so (e.g., Adey & Shayer, 1993; Grotzer & Basca, 2003; Resnick, 1996). Further, it shows that although all students benefit, lower-achieving students tend to gain the most (e.g., Grotzer & Sudbury, 2000; White & Frederiksen, 1995). This is surprising to many educators who guess that because discussions about thinking are abstract, they should be reserved for the most capable learners. On the contrary, there is strong evidence that unpacking thinking has the most dramatic effect for those students who would be unlikely to do it on their own.

The answer is not just good teaching. Research shows that traditional instruction has little effect on deep understanding. Students need the opportunity to grapple with concepts by thinking about their present ideas, comparing and contrasting them to different models or explanations, considering the evidence for each, and eventually accepting the explanations that are most powerful in explaining the

Nine Assumptions That Impede Science Learning

Students of all ages make assumptions when generating explanations although experts are alert to the later possibility in each case.

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.	Bidirectional 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 light 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 variables	The object sinks because of its weight.	Constructed from nonobvious 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 involving delays	The hurtful effects of getting a suntan accumulate and show up after a long 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.

evidence. However, even teaching that uses best practices approaches may not be enough to help students see beyond their default assumptions. Not all activities are equal in helping students revise their assumptions. Students need opportunities to reflect on their default patterns, learn the new causal patterns, and see how they do a better job explaining the phenomenon at hand using the new patterns.

Deeper Science Understanding

No one is claiming that it is easy to teach for deep understanding in science, but it is becoming more and more attainable. Administrators can support teachers' efforts by offering opportunities for teachers to grapple with their own default patterns. Until teachers have dealt with their own default assumptions, they can't help students see how their assumptions impede science learning. This requires dedicated time for teachers to be learners and experience science in a new way.

Administrators can also help teachers envision curriculum development as a three-part process. Teachers need to consider the expert patterns inherent to the scientifically accepted explanation; assess students' current patterns of thinking about the concepts; and analyze or research the cognitive challenges in learning the expert patterns—where students typically have difficulties and, more important, why. Then teachers are ready to develop learning experiences to move students from their naïve explanations toward scientifically accepted ones. By talking about the patterns of causality and making them part of the broader culture, they become less alien and more accessible. As a former student recently remarked, "I carry [the patterns] in the back of my head all the time now and see examples of them everywhere."

There are concrete resources that can help teachers. A small but growing number of free, online resources support teachers' efforts to communicate the expert patterns. For example, StarLogo (Resnick, 1994) is a computer modeling program that helps students discover how behavior patterns, such as those in the cafeteria example, can lead to complex outcomes. The Understandings of Consequence Project with support from the National Science Foundation has developed curriculum units in ecosystems, air pressure, electricity, and density to help students learn the relevant causal patterns as part of the science.

But probably the most important step to making science accessible to all students is to believe that all learners can learn to think better in science. This starts with principals and teachers. If they discover the power of science, they will consciously and subconsciously do more to help students discover that power. PL

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Resources

For information about joining the StarLogo Users Group, e-mail starlogo-request@media.mit.edu or visit www.media.mit.edu/starlogo. The Understandings of Consequence Project's units are available at http://pzweb.harvard.edu/UCP/.

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The Understandings of Consequence Project:
Research Overview

The curriculum materials and the pedagogical approach that grew out of the Understandings of Consequence Project, the *Causal Patterns in Science and Beyond* series, is the result of over ten years of research on student learning funded by the National Science Foundation. This document explains the research behind the program in accessible terms. If you would like more in-depth information or further details on the methodologies involved, we encourage you to visit our research page on the Project Zero website where you will find links to the research studies and specific references for the work.

The work started as a set of research questions. It aimed to address the following puzzles/challenges:

- A long history of research on misconceptions (or alternative conceptions) showed that students typically struggle with fundamental science concepts.
- Our observation in classrooms revealed that despite "best practices" teaching and highly dedicated teachers, students still reverted to nonscientific explanations.
- Even "everyday" scientific concepts assume an extensive repertoire of causal models. In addition, students are being asked to reason about an increasingly complex and global world.
- Students appeared to have limited knowledge about the nature of causality (although developmental research shows that they have more than expected based upon their ideas in science class!) and little opportunity to learn about it.

<u>Do limited notions of causality contribute to students' misunderstandings of everyday science concepts? Will teaching causal patterns enhance their understanding?</u>

<u>Are there ways to teach the patterns and features of causal complexity for today and tomorrow's world in the context of today's curriculum?</u>

Main Research Findings

1. Students often framing the underlying causality in science concepts differently than scientists do.

2. Opportunities to learn the underlying causal patterns improves students' understanding of the science concepts.

3. While explicitly unpacking the causal patterns improves the learning of all students, lower level achievers often improve the most.

4. Learning causal patterns in one topic can transfer to other topics, particularly when teachers engage students in thinking about connections.

Overview of *The Understandings of Consequence Project* Research Phases:

There have been three research phases to date:

- Phase 1: Investigated students' assumptions about the nature of causality within and across different science topics.
- Phase 2: Tested targeted interventions <u>in the context of</u> students' science learning designed to impact how students structured the causality inherent to particular levels of explanation.
- Phase 3: Investigated whether gains, such as those found in phase two, would transfer to new learning.

Phase One Studies:

We interviewed students in the context of their science learning…

- …through open-ended interviews and tasks designed to reveal how they structured concepts.
- …within a number of topics including simple circuits, ecosystems, electricity, density, pressure, force and motion, and evolution.
- …from third through 11th grades.

Phase One Findings:

- Students make assumptions about the nature of causality that influence their ability to learn science concepts. (See list of default assumptions.)
- Students' tend to assimilate information about complex concepts into simpler causal structures thus distorting the information.
- This was so for both "everyday science" and for complex science concepts.
- This was so before, during, and after learning.

Phase Two Studies:

Across topics and grades, we worked with our teacher collaborators to develop curriculum that would teach the underlying causal patterns in service of the science. We compared the performance of students in classrooms with three different approaches

1. Causal Activities (RECAST) and Discussion
2. Causal Activities (RECAST) Only
3. Best Practices Control Group

All classes used "best practices" science units that included:

- extensive modeling by students.
- evaluating evidence.
- Socratic discussion.
- dynamic computer models.
- attended to students' evolving models.

But some added causal activities or causal activities plus causal discussion.

Phase Two Findings:

Across most topics, introducing RECAST activities significantly benefited student performance.

- For some topics, RECAST activities alone were not enough to make a difference and there was significant benefit to adding explicit discussion of the causality. The activities can be sufficient to learn less complex patterns and causal discussion appears necessary when the patterns are most counterintuitive.
- RECAST activities plus discussion benefited students across different achievement levels on topics with difficult causal concepts. Low achievers (as defined by their teachers) made the most dramatic gains.
- Effect sizes varied across topics depending upon the complexity of the causality to be grasped (higher effect sizes with more difficult forms) and depending upon other sources of difficulty.

Phase Three Studies:

Phase Three investigated whether learning about the underlying causality could make a difference beyond the concepts for which it was taught—would it transfer to new learning? We asked:

1. Does learning about causal patterns transfer between topics when the causal patterns are the same (for instance, many density and air pressure concepts have an underlying relational causality)?
2. What about when they are different? Might students begin to notice other forms of causality by comparison?
3. Are there any ways that it might help them generally in future learning (such as encouraging them to think more deeply, or by offering ideas about what it means to learn well, etc.)?

Phase Three Findings:

- There was some transfer of learning even without any special support when the causal patterns were the same.
- When teachers supported transfer (for example, by asking students, “Are there any other places where you might have seen this causal pattern?” Or “Think about your thinking, what kind of causal pattern are you using?”), there was a good amount of transfer when the causal patterns were the same and even some when the patterns were different.
- Good results were obtained when students worked with materials that helped them to think about the transfer of causal patterns, but that teacher support and discussion was even better.
- There was evidence that students were better prepared for learning in a general sense, but it was inconclusive in this study.

Our work is on-going. Check back on our project page on the Project Zero site to hear about new research that we are involved in and for a link to the *Causal Patterns in Science* Website.