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).

Tina A. Grotzer (tina_grotzer@pz.harvard.edu) is a principal investigator for Project Zero at the Harvard Graduate School of Education. She conducts research on science learning and cognition in K–12 classrooms and previously taught and coordinated programs in public and private schools.

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

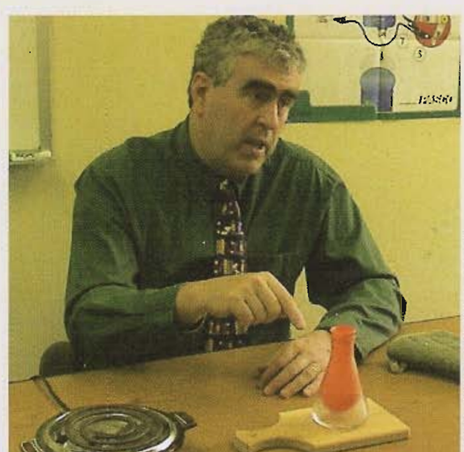
If students aren't reasoning like scientists, how are they reasoning? Over the past 25 years, researchers have been investigating students' ideas in science. A wealth of research shows that students come to school with naive but firmly rooted theories of how the world works (e.g., Driver, Guesne, & Tiberghien,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



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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/.

AUTHOR'S NOTE

The ideas in this article were supported in part by Grant No. REC-9725502 and REC-0106988 from the National Science Foundation to Tina Grotzer and David Perkins. Any opinions, findings, conclusions, or recommendations are those of the authors and do not necessarily reflect the views of the National Science Foundation.