Negotiating the Funnel: Guiding Students Toward Understanding Elusive Generative Concepts

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There are some topics, such as force and motion, the nature of matter, and probability, that my students just don't seem to understand deeply. Some students do ... but not most of them. They might do all right on multiple choice tests, but as soon as I ask them a question that scratches the surface, they don't know how to answer it. Or they tell me the same kinds of things that they said before we studied the topic. I just don't know what to do!

Understanding can be elusive. We have heard numerous teachers echo the sentiments above. Certain science and math concepts are especially difficult to grasp, and many students never learn to understand them deeply. This happens despite concerted teaching and learning efforts. To complicate matters further, some of these concepts, such as Newton's laws about force and motion, or the nature of probability, are key to a multitude of other understandings.[1] Learning these concepts can be compared to trying to make the ball in a pinball game enter an upside down funnel shape. The narrow opening is hard to negotiate, but the payoff on the other side is big. For instance, understanding density is key to comprehending phenomena such as convection currents, floating and sinking, weather patterns, ocean currents, habitats at the points where fresh and salt water meet, and plate tectonics. If students learn these key concepts well, they can be highly generative—helping students to understand many other concepts. If students do not learn them, they serve as barriers to many other understandings. Teaching for deep and generative understanding requires that teachers attend to these important, but often elusive concepts.

This article explores the nature of these difficult, yet potentially generative concepts and some of the inherent conceptual problems they pose for learners from a cognitive science perspective. It begins with a brief review of some of the arguments made in the study of student misconceptions (or what are now commonly called "alternative conceptions").[2] It goes on to consider why certain concepts are so elusive. It then explores one type of cognitive challenge students grapple with that we are researching in detail: mismatches between the causal expectations that students bring to their learning and those embedded in the science curriculum. We refer to "causal expectations" and "causal assumptions" throughout the paper. We use these terms interchangeably to mean the assumptions that students make about the nature of causes and effects and the subsequent expectations that students hold for how causes and effects implicit in scientific phenomena should behave. This analysis represents some of our initial work on the Understandings of Consequence Project. In collaboration with classroom teachers, we are examining students' causal expectations and how they affect science learning at different ages. This research is in its very earliest stages; therefore, the educational implications of the research are not yet entirely clear. However, we offer a few suggestions for ways to guide students through the narrow end of the funnel into the rich areas of understanding beyond, based on the early implications of the research. We also provide three brief sketches of practice from our work with students and teachers. (See accompanying figures.)

A Brief Overview of the Research on Misconceptions

During the past two decades, researchers have studied students' misconceptions about a wide variety of topics. They have found that students often bring their own intuitive theories to their school learning and that these theories compete with the accepted scientific theories in the curriculum. In addition, students often develop nonscientific theories in the context of science classes as they make personal sense of what is being taught.[3] Students' theories, developed from their experiences and observations, can be highly resistant to change. Students generate such theories as a way of making sense of their experiences or observations, so it follows that the resulting theory "works" for the student in question. Making sense of one's observations is an important scientific skill. So why, then, does making sense so often go wrong and result in misunderstandings?

One source of misconceptions is developmental limitations. Children hold limited information about the world around them and when making sense, generalize from their limited knowledge base. Students also hold undifferentiated concepts.[4] For instance, the words "heat" and "temperature"[5] or "matter" and "weight"[6] might mean the same things to them. Everyday language often reinforces or otherwise complicates these undifferentiated concepts.[7] This is not just an issue for children. Concepts that are closely related but carry subtle, yet important, distinctions are easily blended in a person's mind. Instruction needs to attend to helping students build such distinctions.

A lack of understanding of the nature of science and of the conventions and knowledge-building rules of the discipline are also an issue. Young children are often comfortable with customized theories—that is, explanations that fit only a single event—and do not perceive the scientific value of a coherent, parsimonious theory to explain like cases. Building customized theories can result in weaving long and intricate explanations tied to the specific contexts. Students often reason in a context dependent manner–explaining what they presently observe while holding what a scientist would perceive as contradictory explanations for similar cases.[8]

Other misconceptions result from the wrong sorts of teaching and learning practices. Curriculum that skims the surface and does not enable students to actively perform their understandings leads students to leave the blanks blank or to fill them in erroneously. Some concepts are not easily learned from the kinds of school models that are available to students. For instance, in many classrooms, students are asked to speculate about what creates the seasons, the phases of the moon, and the illusion of the sun rising and setting by using models that are manipulated in the front of the class.[9] Two inherent difficulties for which students typically receive little support are the amount of information students must hold in their heads and think about and the perspective-taking shift that students must engage in to place themselves on the model and reason about what they see by translating it back to what they see on Earth. Moreover, all models break down at some level, and unless teachers and students are helped to see both what models explain and what they leave out, misconceptions may arise.

Developmental limitations and ineffective teaching practices can account for some misunderstandings. But what about concepts that are elusive for most people despite good teaching and good information about the world? Some concepts are so difficult that even if students learn the deep story, if they later forget it and try to re-deduce the answer, they may go astray again. Why are some concepts elusive in this way?

Elusive Concepts Are Counterintuitive to Perceptual and Causal Expectations

Many elusive concepts[10] are highly counterintuitive. They require students to reason in ways that run counter to their perceptual and causal expectations. Consider the following question: “If you had two like objects and you simultaneously dropped one straight down and shot the other horizontally from the same level, which would hit the ground first?” What are your first thoughts? Most people are inclined to say that the one that was dropped straight down would hit the ground first. The other one had farther to travel, didn’t it? The scientific answer to the question, that both objects would hit the ground at the same time because the horizontal motion does not affect the downward motion, is counterintuitive to most people.

Similarly, consider another question: “If you dropped a package from a moving plane, where would the package fall: directly beneath the spot where it was dropped, slightly behind the spot where it was dropped, or slightly ahead of the spot where it was dropped?” Intuitively, people tend to think that the package will fall either directly below or slightly behind where it was dropped. However, the scientific answer to the question is that it will fall slightly ahead of the spot where it was dropped. This is because the package is moving at a certain velocity (speed and direction) when it is dropped from the plane. However, an intuitive response may fit with what people have perceived in the past. People may rely on past perceptions without considering their perspective or frame of reference as a variable. Depending upon where they are as an observer, they are likely to notice different things. For instance, if they were in the plane, they might perceive the package as trailing far backwards (although not falling behind the mark) because the plane continues to have the thrust of the engines so it has a greater velocity than the package as soon as the package leaves the plane. Similarly, an observer not in the plane might have the illusion that the package would fall behind as appears to happen to bombs falling from a plane in an old war movie. Because the plane (with the continued thrust of the engines) outpaces the package, it appears to fall behind or on the spot instead of somewhat in front of it. Perception deeply influences reasoning[11] and the embedded perspective-taking shifts may be missed, leading many people to the wrong conclusions. However, intuitive, yet wrong, conclusions are common because they make sense based on what people typically perceive.

Students hold similar intuitively-based, yet scientifically wrong, conceptions. For instance, many students think that vacuums “suck.”[12] This certainly fits with one’s perception of what is happening. What appears perceptually as a pull is scientifically conceived of as a push. The air pressure in the tube is less than that surrounding it and so air is in a sense pushing into the tube. Understanding this phenomenon relies upon recognizing the existence of air pressure as a causal agent, although it is a nonobvious one. Historically, scientists did not recognize the existence of air pressure until 1630, when Torricelli, a young assistant of Galileo's, became interested in the puzzle of why piston pumps at the top of mineshafts would not pump water higher than 32 feet. He deduced that air must be pressing on the pool of water at the foot of the mineshafts and that air pressure was responsible for the height to which the water could be pumped.[13]

Students' conceptions fit with their perceptual and causal expectations and often are part of a cohesive framework that can compete with scientific explanations that are introduced to them. For instance, it is not uncommon for students and adults to rely on the principles of Aristotle rather than those of Newton to solve problems about force and motion. According to Aristotle, motion was maintained by forces.[14] The source of the forces was the air around a projected object (such as a stone thrown in the air) which pushed it along on its way. According to Newton, a body stays at rest or in motion in a straight line and at constant speed unless a force acts upon it. Most students believe, as did Aristotle, that constant motion requires a constant force and that a force must continue to act on an object if it is to continue in motion even under (simulated) friction-free conditions.[15] Students also believe that if a body is not moving there is no force acting on it. Such interpretations fit the perceptual information available in the context of everyday experiences. Ideas such as these are reinforced over time, thus becoming deeply embedded in how people reason about causes and effects. Constant reinforcement firmly establishes these ideas internally, and they have been called "gut dynamics."[16]

Many researchers have argued that the only way to encourage students to let go of their robust, personal theories is to introduce competing frameworks and help students see that these hold more explanatory value. Indeed, this is the nature of how knowledge is generated in science. Increasingly powerful explanatory models take the place of less powerful ones. Yet, learners are not always willing to adopt new models. Young students and adults alike tend to ignore counter-evidence and weigh supporting evidence more heavily. They often seek support for their current ideas and ignore evidence to the contrary. The assumptions that people carry into any given situation influence what they perceive and how they interpret what they perceive. Introducing competing frameworks may be an important part of the answer, but it's clearly also important to unpack implicit assumptions that students bring to their learning and that limit their acceptance of more powerful explanatory models.

While some intuitive theories can be highly idiosyncratic, many of them do follow particular patterns of perception and reasoning that tend to make sense to large groups of students. In some cases, the intuitive theories students generate resemble those that scientists of earlier generations developed.[17] Exploring the cognitive patterns that students engage in (and the implicit assumptions that they entail) in relation to particular patterns embedded in science concepts can help teachers to see where students get stuck on these elusive concepts and why. This, in turn, can help teachers to design learning experiences that enable students to see beyond them.

One set of cognitive patterns that students bring to learning science includes their implicit assumptions and subsequent expectations about the nature of causality. Rosalind Driver and colleagues have outlined many characteristics of student thinking that give rise to misunderstandings.[18] A number of these relate to how students think about causality. For instance: 1) Students tend to notice changes as opposed to steady states. Therefore they ignore or do not see a need to explain systems in equilibrium. 2) Student focus tends to be fairly limited. They often seek out local variables and perceptually salient characteristics to explain what is going on, when often what is needed is a more systemic view. 3) Students engage in linear causal reasoning. This means that they look for sequential chains of effects. Often, a more systemic pattern of interaction is in play. There has been an increasing interest in how assumptions such as these, or "core causal intuitions" as David Brown refers to them, influence students' ability to learn elusive science concepts.[19] The role of students' causal expectations in learning difficult science concepts is the focus of our current research. We draw upon this work and the extant research to offer an in-depth look at how students' cognitive patterns interact with particular patterns embedded in science curricula to create difficulties and make understanding elusive. This work suggests that helping students examine their implicit causal assumptions and to try out other sets of assumptions is an important piece of introducing competing frameworks and helping students to accept them.

How Elusive Concepts Challenge Students' Causal Expectations

Our research attempts to tease apart the causal expectations and types of models that students bring to learning these difficult concepts from those expectations and models embedded in the concepts as they are taught in the school curriculum. As students approach learning opportunities, they bring a whole set of implicit assumptions about the way things work. Some of these assumptions have to do with the nature of cause and effect. More often than not, students are unaware of their implicit assumptions. A mismatch between students' causal expectations and causal models embedded in science concepts can generate a variety of misconceptions and create barriers to learning. What are some of the features of such mismatches? Let's compare what students tend to expect with what the school science curriculum demands and examine the implications of the tension between them.

Students tend to expect obvious causes and obvious effects.

From a scientific standpoint, causal mechanisms and effects are often nonobvious. However, students typically look for noticeable causes and effects. When the scientific cause of an event is not obvious, students often look for plausible causes rather than suspecting that there might be a nonobvious cause. (See Figure 2.) For instance, when fourth graders were asked what they thought caused lightning, a number of them said that it leaks from electrical wires and drew diagrams showing the electricity coming from electrical poles and electrical wires. We wouldn't expect the majority of fourth graders to know the scientific explanation. Lightning is the result of a buildup of electrons in portions of clouds and the subsequent balancing out of electrical charge as electrons are attracted to protons elsewhere (at the same time that the electron partners of those protons are repelled by the buildup of electrons in the cloud and air.) While some students acknowledged that something caused lightning, but said that they didn't know what it was, many attributed it to what they could see. It certainly can be puzzling when an event occurs with no obvious cause. In the air pressure example above, early scientists were puzzled about the mysterious leveling off of water in the tubes at 32 feet. The cause was entirely nonobvious and therefore elusive to most. However, the tendency of students to seek an obvious cause limits the likelihood that they will suspect that there might be a nonobvious cause and will seek it out.

Confronted with nonobvious effects, people are less likely to notice the effects or realize that two or more events are causally linked. For instance, giving a plant less fertilizer may slow its rate of growth, but unless there is a control against which to measure the difference in order to make it obvious, people are unlikely to recognize the effects of reduced fertilizer. Similarly, subtle temperature changes may affect the behavior of the crickets in the class insect tank. However, students are unlikely to link the two unless the changes are obvious or noticeable to them. The obviousness of effects is linked to the spatial and temporal distance of effects to their causes. This is discussed further below.

Students tend to notice and think of changes, but not steady states, as caused.[20]

From a scientific standpoint, steady states are thought of as caused. Students often attach importance to changes that they observe. They notice and then look for ways to explain the change. From a scientific stance, it also makes sense to ask what causes steady states. For instance, what causes a cup to stay on the table? The gravitational attraction between the cup and the earth, the cup and the table pushing on each other, and the absence of other forces acting upon the cup cause it to stay where it is. Assigning causes only to instances of change can lead students to assign causality differently from the way that a scientist would. When teachers speak of forces, students expect to see an effect. In contrast, when there is no movement, students expect that there is no cause or no force. If there is no obvious action, students consider it pointless to look for forces in play.[21] For example, a scientist might look at a suspension bridge as a complex interaction of forces that cause the bridge to hold together, whereas students might look for causes only when the bridge moves in certain ways or if it collapses. Students might look for the presence of a cause of a collapse, whereas scientists might look for the absence of a balancing force as the cause. Expecting noticeable causes and effects can work against recognizing that steady states are caused. As teachers, we may exacerbate the situation if we focus only on changes or dramatic events.[22]

To complicate matters, scientists explain certain phenomena using laws or constraints. For instance, students often view constant movement as caused not just initially, but continually. If an object continues to change position (even if at the same velocity), something must be causing it to change position. However, according to Newton, an object in motion stays in motion unless other forces act upon it. Students emphasize an active agent as the cause of motion and tend to believe that constant motion is caused by a constant force, so that when something stops moving, they say that the force that caused it to move in the first place is used up and that is why it stops moving. A scientist takes the continued movement as a given (once the object is in motion, it stays in motion) and seeks the forces that acted upon it to cause a change in its velocity when it stops.[23] Scientists focus on forces acting to cause it to stop rather than on cessation of the cause of motion.

Students tend to reason about local causes.[24]

Causes and effects are often distant in time and space. When students search for causes of events in science, they tend to look close to the effect. This can result in intuitive theories that make it hard for them to understand a variety of science concepts. For instance, understanding the cause of acid rain, global warming, and the movement of a needle in a compass all require a search for causes that are distant in time and space from the effects. Research shows that when learning about branching electrical circuits, students show a tendency to think locally about the circuits and to ignore the effects of variation at one point upon the whole circuit.[25]

Local causal reasoning reflects a tension between efficiency and sensitivity to extended patterns of cause and effect. It is typically most efficient to look for local causes rather than automatically to consider temporally and spatially distant factors or systemic relationships. In contrast, a tendency toward efficiency or finding the factors that minimally satisfy to explain an event can result in limited sensitivity to more extended and/or complex effects. In addition to looking for causes that are local to the effect, students also tend to assume that a cause is necessary when it may only be sufficient and numerous other sufficient causes exist. This means that while one cause can lead to the effect, so can a number of others. Or students may assume that one factor is causal when there are a number of contributing causes.

Time delays and spatial gaps can be difficult for students to recognize and deal with. Students often don’t notice that two events co-vary if there is a gap in time between them. Instead, students choose events that occurred close in time as the cause of an effect, rather than events that consistently co-vary with the other event but are removed in space and time.[26] Students also have difficulty perceiving a cause and effect relationship when there is a lack of spatial contact. The closer in proximity a potential cause is to an effect, the more likely it is to be chosen as the actual cause.[27]

Students tend to expect simple linear, sequential causal patterns.[28]

Students often bring linear causal expectations to phenomena that are only deeply understood in a scientific sense by applying a more complex causal model. For instance, when learning about electricity, many students apply a linear, consumer-source model to analyze what works when they connect batteries and a bulb, rather than the cyclic model taught in units on electric circuits. The fundamental concept to be understood is that electricity requires a complete circuit or cycle. Students’ initial attempts at connecting the battery and bulb often reflect a linear model. They are surprised when they attach one wire from the battery to the lightbulb and it does not light up. Even when students are taught that they must have a complete circuit or circle, if they are not helped to see how the model explains a variety of phenomena, they may distort the cyclic model to retain their linear expectations. For instance, students claim that the second wire is a safety ground and isn’t really necessary for the bulb to light up or that the current travels up both wires to the bulb. Linear relationships are often a most efficient first pattern to seek out, as is also the case with local causal reasoning. However, when students implicitly reduce more complicated phenomena to linear sequential patterns, some of the causal story may be lost and that loss can result in misunderstandings that hinder deep understanding of the subject matter.

When learning about electricity, even students who hold a cyclic model, often expect a sequential cyclic effect and tend to think increases in the length of the wire or row of batteries will result in perceptibly longer periods of time until the bulb lights. The school-taught model requires them to recognize that there are already electrons all along the circuit and that the flow and resistance cause the bulb to light as the entire thing moves–like the way a whole bicycle chain moves at once.[29] The bicycle chain, like the electrical current, has some transient, imperceptible delay as it gets started, but the cause of a bicycle moving is the simultaneous cyclic movement of the gears (as it is in the bulb lighting due to the steady state of the flow of current.) Understanding the steady state necessitates a cyclic, simultaneous causal model as opposed to a sequential, cyclic model. When thinking about complex circuits, students fail to consider conservation of current because they use a time-dependent or sequence model to determine how changes affect the current.[30]

Many other examples exist. Students asked to reason about sinking and floating tend to focus on the density of the object to be floated, not on the density of the object relative to the density of the substance it was placed in. (See Figure 3.) They apply a simple linear model of cause and effect rather than a relational model of cause and effect.[31] Students think of hot and cold as entities that affect each other in a linear causal manner, rather than in a systemic interaction.[32] In thinking about relationships embedded within ecosystems, students notice chains rather than interdependencies, systems, and cycles.[33] Children younger than 9–12 tend to break down cyclic or re-entrant causality into sequences of cause and effect in which the sequence ends and then starts over again before they grow to see it as an integrated whole.[34]

Not grasping the underlying causal pattern makes it difficult for students to deeply understand the logic of how to apply certain concepts. In understanding electricity, if students do not apply a cyclic, simultaneous model, they will not, for instance, understand the behavior of parallel and series circuits. These students may be surprised by the outcomes of certain actions on a variety of systems (e.g. ecosystems, immune systems, and so on) if they implicitly rely on a linear model.

Students tend to focus on the current situation rather than on processes or patterns of effects.

Scientific reasoning often requires a focus on processes and patterns of effects. Students often miss the broader pattern of effects. This relates to missing effects that are distant in space and time, as mentioned above. For instance, consider the following. What if you asked students whether or not this would be a good deal? Their parents pay them a penny to do a task on the first day and then the amount that they receive doubles each day from the previous day’s amount. Most students would focus on the initial earnings (one penny, then two, then four) and would not consider it a good deal. Students who focus on the pattern rather than the amounts quickly discern the pattern of exponential growth and realize that the plan would soon bankrupt their parents. Beyond this, students need to realize that the pattern of growth in this example is not linear.

Failure to recognize the non-linear pattern can lead to attempts to affect the current situation or the initial, limited outcome rather than longer term patterns of events that have been set in motion. People often extrapolate from the moment rather than review the process dynamics that they perceive over time and extrapolate from those. Research shows that adults also typically regulate situations or things but not the dynamics of a system.[35] For instance, the disaster at Chernobyl resulted in part from attempts to regulate the condition of the system at the particular moment in time rather than regulate the pattern of its dynamics.[36] When people make predictions, they often rely on a linear development model rather than choose from a wider set of prediction models such as those that include acceleration, deceleration, growth rates, saturation points, etc.[37] Scientific and mathematical concepts such as exponential growth seem counterintuitive to students in part because students focus on individual events rather than the pattern of the processes.

Students tend to expect absolute correspondence between possible causes and effects as an indication that a causal relationship exists.

From a scientific stance, a causal relationship may be embedded in an event that does not reliably occur due to a variety of complicating variables. These relationships are hard for students to perceive as causal. In a lesson on lightning, fourth graders discussed why lightning typically strikes in high places and how an explanatory model of electrons and protons balancing out could account for that. However, after one student explained how she had seen lightning strike in a low place, a number of students found it difficult to accept the causal model of what happens when lightning strikes in a high place. They interpreted the complicating factor of uncertainty or unreliable cause as disconfirming of the causal relationship. Similarly, researcher Charles Kalish found that younger students do not understand the uncertain aspects of germ transmission and how people get sick.[38]

Research in cognitive development shows that fourth grade children are just beginning to use frequency-based strategies (e.g., ratios, chance, reliability), but that their use is not yet very sophisticated.[39] Students use the information available to them to deduce the existence of causal relationships. Younger students have difficulty recognizing causal relationships in instances of partial correspondence between causes and effects. They tend to use instances of partial correspondence as disconfirming of the causal relationship rather than look for instances of a contributing cause or an unreliable cause in play. This is a hard lesson of science, that the predictive value and descriptive value of causal information can be at odds, especially when a variety of other variables are involved. One might be able to describe what happened in a particular case, but that does not mean that there is absolute correspondence so that the next time, one can expect what absolutely will happen.

These six tendencies frame some of the expectations that students bring to understanding scientific concepts and explain why in some instances the concepts are counterintuitive. Our research delves into how these expectations play out as students learn particular science topics and what students need to learn in order to move beyond simple, linearly-patterned expectations. We are investigating what types of causal patterns students need to consider in order to master more powerful scientific explanations.

Guiding Students Into the Upside Down Funnel

So what does our work suggest that teachers can do to guide their students toward deeper understanding of elusive science concepts? While the work is still in its infancy, it does point to patterns of student reasoning that can help teachers anticipate types of difficulties that students will encounter and plan experiences to guide them through these challenges.

For instance, teachers can design curriculum that takes into account and builds upon students' causal expectations. The example in "Making Nonobvious Causes Obvious" (Figure 2) outlines a lesson taught by a fourth grade science teacher that *recognizes and builds on the causal expectations* that children bring to their learning. It makes an important *nonobvious causal mechanism obvious*. A lesson that does this will be more difficult to design in some cases than in others. In the everyday context of a science classroom, it may be hard to demonstrate that forces are involved in static situations, for instance. However, in designing curriculum, it is useful to ask, What are the nonobvious causes that my students are likely to ignore and how can I make them obvious? Further research can help illuminate causes embedded in the science curriculum that are nonobvious to students.

Teachers can also instruct students to be alert to a broader set of causal patterns. They can make students aware of causal expectations that may limit them and offer them other causal models to consider. These models may be of a variety of types, for instance, branching, cyclic, equilibrational (i.e., balancing), relational, and so on. The figure entitled, "Exploring Models of Density" (Figure 3) offers a glimpse of some of our early attempts to do this with an eighth grade science class.

David Perkins and colleagues[40] have written about the importance of teaching students the epistemic games of science—the implicit rules and assumptions of knowledge generation in the field. In a sense, these are the rules by which scientists play. Teachers can offer students explicit access to these rules by discussing them and helping students see their importance. For instance, teachers can explain to students the need to consider probability when determining causal relationships, the possibility of contributing variables, and so on. Science class discussion can combine focus on content, various models, and the underlying principles involved in thinking like a scientist.

Yes, understanding can be elusive and teaching for understanding can be a challenging undertaking. However, realizing the counterintuitive nature of the understandings students must learn and being alert to limiting assumptions that students might be making increases the possibility that teachers can help students maneuver their way through the narrow end of the funnel and into the rich areas of understanding beyond. The generativity of these challenging concepts suggests that they are well worth the investment of additional effort in helping students to learn them.

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[1] David Perkins has referred to these concepts as “targets of difficulty” and “bottleneck concepts.” A “bottleneck” refers to “a narrow route” or “a situation that halts progress.”

[2] Many researchers today refer to “alternative conceptions” or “preconceptions” rather than “misconceptions” to signal that children’s theories are authentic and in their own terms reasonable constructions. Acknowledging this, we use the older term “misconceptions” because we expect that teachers will initially recognize them as such.

[3] Howard Gardner synthesized much of this research and explored the how the nature of children’s thinking can lead to intuitive theories and scientific misconceptions in his book, *The unschooled mind: How children think & how schools should teach*. New York: Basic Books, 1991.

[4] Driver, R., Guesne, E., & Tiberghien, A. (1985). Some features of children’s ideas and their implications for teaching (pp. 193–201). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children’s ideas in science*. Philadelphia: Open University Press.

[5] Tiberghien, A. (1983) as cited in Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children’s ideas.* New York: Routledge.

[6] Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the concepts of size, weight, and density. *Cognition, 21*, 177–237; Smith, C., Maclin, D., Grosslight, L., & Davis, H. (1997). Teaching for understanding: A study of students’ preinstruction theories of matter and a comparison of the effectiveness of two approaches to teaching about matter and density. *Cognition and Instruction, 15*(30) 317–393; Smith, C., Snir, J., & Grosslight, L. (1992). Using conceptual models to facilitate conceptual change: The case of weight-density differentiation. *Cognition and Instruction, 9*(3), 221–283.

[7] e.g., Bell, B. & Freyberg, P. (1985). Language in the science classroom. In R. Osborne & P. Freyberg (Eds.), *Learning in science: The implications of children’s science* (pp. 30–40). Auckland: Heinemann.

[8] Driver, R., Guesne, E., & Tiberghien, A. (1985). *Children’s ideas in science*. Philadelphia: Open University Press.

[9] Schneps, M. N. (1989). *A private universe*. Santa Monica, CA: Pyramid Film & Video.

[10] Here we use the term “concepts” —which is familiar to teachers—to denote the broader notion of a “conception” or the sum of a person’s ideas and beliefs concerning something. We take a “conception” to refer to a whole conceptual system–the concepts, claims, models, arguments, and other elements that go into making up the conception.

[11] Driver et al., 1985.

[12] Driver et al., 1985.

[13] Burke, J. (1978). *Connections*. Boston: Little Brown & Company.

[14] Driver et al., 1985.

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[15] Langford, J. M. & Zollman, D. (1982). Conceptions of dynamics held by elementary and high school students. Paper presented at the annual meeting of the American Association of Physics Teachers, San Francisco.

[16] Claxton, G. L. (1984) as cited in Driver et al., 1994; Driver et al., 1985; Osbourne, R. (1984). Children's dynamics. *The Physics Teacher, 22*(8), 540-548.

[17] Here we simply refer to resemblances between student theories and earlier scientific theories. The stronger case of the argument, that students' growth in understanding might recapitulate or follow the same path as that of scientific thinking in a historical sense, has raised a fair amount of controversy in the field.

[18] Driver et al., 1985.

[19] Brown, D. (1995). *Concrete focusing and refocusing: A cross-domain perspective on conceptual change in mechanics and electricity*. Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, April 18–22.

[20] Driver et al., 1985.

[21] Gunstone, R. & Watts, M. (1985). Force and motion (pp. 85–104). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science*. Philadelphia: Open University Press; Minstrell, J. (1982). Explaining the "at rest" condition of an object. *The Physics Teacher, 20*, 10–14.

[22] Personal communication, Nancy Blasi, February 23, 1999.

[23] Gunstone & Watts, 1985; Langford & Zollman, 1982.

[24] Driver et al., 1985.

[25] Shipstone, D. (1985). Electricity in simple circuits (pp. 33–51). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science*. Philadelphia: Open University Press.

[26] Mendelson, R. & Schultz, T. (1976). Covariation and temporal contiguity as principles of causal inference in young children. *Journal of Experimental Child Psychology, 22*, 408–412.

[27] Bullock, M., Gelman, R., & Baillargeon, R. (1982). The development of causal reasoning (pp. 209-254). In W. J. Friedman (Ed.), *The developmental psychology of time*. New York: Academic Press.

[28] Driver et al., 1985.

[29] Teaching more complex models does not imply that these do not also break down at some level of explanation. The process of science involves trading off for increasingly powerful explanatory models. The cyclic, simultaneous model, for instance does not explain that there is an imperceptible (less than a nanosecond) delay in the time between turning on the switch and the lightbulb lighting due to the compression of the distances between electrons as the current starts to flow.

[30] Shipstone, 1985.

[31] Houghton, C., Bell, B., & Grotzer, T.A. (1999). Conceptualizing density: Moving toward a relational systemic model. Manuscript in preparation.

[32] Erickson, G. & Tiberghien, A. (1985). Heat and temperature (pp. 52–84). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science*. Philadelphia: Open University Press.

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[33] e.g., Griffiths, A. K. & Grant, B. A. C. (1985). High school students' understanding of food webs: Identification of a learning hierarchy and related misconceptions. *Journal of Research in Science Teaching, 22*(5), 421–36; Grotzer, T. A. (1989). *Can children learn to understand complex causal relationships?: A pilot study*. Unpublished qualifying paper. Cambridge, MA; Harvard University; Grotzer, T. A. (1993). *Children's understanding of complex causal relationships in natural systems*. Unpublished doctoral dissertation. Cambridge, MA: Harvard University; Webb, P. & Boltt, G. (1990). Food chain to food web: A natural progression? *Journal of Biological Education, 24*(3), 187–190.

[34] Grotzer, 1993; Smith, E. L. & Anderson, C. W. (1986, April). *Alternative conceptions of matter cycling in ecosystems*. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, San Francisco, CA.

[35] Dorner, D. (1989). *The logic of failure*. New York: Metropolitan Books; Driver et al., 1985.

[36] Dorner, 1989.

[37] Dorner, 1989.

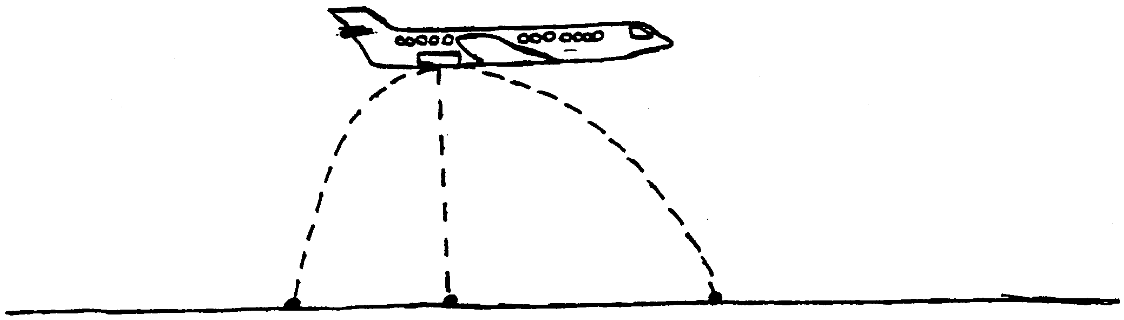
[38] Kalish, C. W. (1998). Young children's prediction of illness: Failure to recognize probabilistic causation. *Developmental Psychology, 34*(5), 1046–1058.

[39] e.g., Siegler, R.S. (1975). Defining the locus of developmental differences in children's causal reasoning. *Journal of Experimental Child Psychology, 20,* 512–525.

[40] Collins, A. & Ferguson, W. (1993). Epistemic forms and epistemic games. *Educational Psychologist, 28*(1), 25–42; Perkins, D. N. & Simmons, R. (1988). Patterns of misunderstanding: An integrative model of misconceptions in science, mathematics, and programming. *Review of Educational Research*, *58*(3), 303–326.

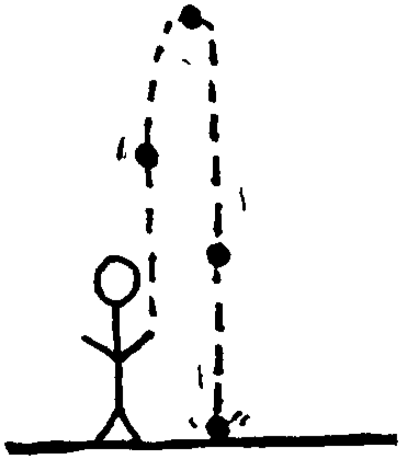
Figure 1 - Examples of Counterintuitive Problems with Force and Motion

If you dropped a package from a moving plane, where would the package fall?



Answer: Although most people intuitively think that the package will fall either straight down or behind where it was dropped, the package will actually fall slightly ahead of the spot where it was dropped since the package continues to move with a certain velocity after it leaves the plane.

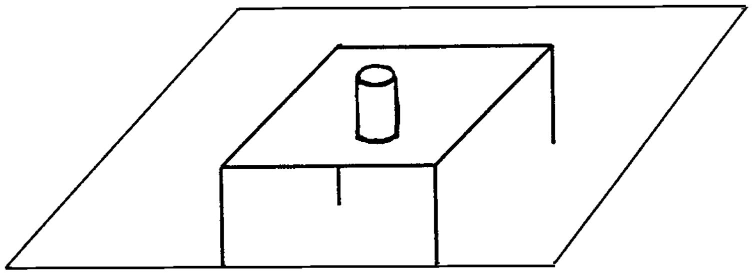
If you throw a ball up into the air, what force(s) are acting on the ball during its flight?



Answer: Most people correctly identify gravity and air resistance as two forces that act on the ball. However a third force is also commonly identified, the force of the throw as the ball moves upward, which is incorrect. This “impetus” belief in which the force stays with the ball is a commonly held erroneous perception for both students and adults.

Figure 1 - Examples of Counterintuitive Problems with Force and Motion

What forces are acting on the cup as it rests on the table?



Answer: Many people think that since there is no movement, there are no forces acting. Or they reason that gravity is the only force acting causing the cup to sit on the table. Scientists, however, reason that the cup is exerting a force on the table and the table is exerting an equal and opposite force on the cup. Expecting an effect in situations such as this leads to misinterpretations of steady states as uncaused.

Figure 2. An example of a teacher making nonobvious causes obvious

Making Nonobvious Causes Obvious

Nadine Solomon's fourth grade science class has been exploring the question, "Is there air all around us?" The students know that scientists say that there is, but are they convinced? "Let me show you some things that convince me and you can think about whether they convince you that there's air all around."

Mrs. Solomon explores a number of concrete examples with students. First she scoops a large garbage bag through the air and squeezes the opening closed, trapping air inside. "Is this evidence?"[1] she asks. The students agree that if there was not air or at least something in the bag, it would collapse instead of resisting her push. As she lets the air out of the bag, she forces it out quickly near a student with long hair and the class witnesses the visible effect of a student's hair blowing back.

Next, Mrs. Solomon puts an apparently empty, upside down jar into a large, clear container of water, capturing the air inside the jar. Students see that the water level in the jar is only a centimeter or so high. Then, she removes her finger from a hole in what is now the top of the upside down jar and invites each student to feel the escaping air. Each time, she returns to her question, "Is this evidence?"

Mrs. Solomon invites students to try to pull a plastic bag that is inside a can and tightly sealed to the rim of the can. They puzzle over why it is so hard to pull. What might be pushing the bag into the can? "Is this evidence of air?" Mrs. Solomon asks. Finally, she takes two identical pieces of paper and crumples one. She ask students what they think will happen when she drops them. "The crumpled one will fall faster" guesses one student. "How might that be evidence that air is all around us?" Mrs. Solomon asks. A student responds, "The flat one has more air to push through as it falls." Each example is focused on making the effects of air's behavior perceptible. Afterward the students write in their journals, explaining whether or not they believe that air is all around, and which, if any, of the examples convinced them.

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[1] These demonstrations may not involve evaluating evidence in the strong sense of students making predictions from alternative competing theories and evaluating which theory fits with the outcomes. However, they are evidence in the sense of making nonobvious causes more salient.

Figure 3. An example of exploring models of density

Exploring Models of Density

Eighth graders were exploring the concept of density with Project Zero researchers, Belinda Bell and Carolyn Houghton.[1] After interviewing several of them about their understanding of sinking and floating, Ms. Bell, noticed that a number of the students attended only to the density of the object and not to the density of the liquid it was floating in. To probe this further with all of the students in the study, Ms. Bell and Ms. Houghton engaged them in the following activity.[2] Ms. Bell said, “Here we have two beakers. They contain different liquids. I have two pieces of wax. They are both made of the same kind of wax. I will drop the smaller piece of wax into beaker A and the larger piece of wax into beaker B.” The students observed that the small piece of wax floated and the large piece of wax sank. Ms. Bell asked, “Why did the small piece of wax float in beaker A? Why did the large piece of wax sink in beaker B?” One student noted, “The wax floated in beaker A because it was light and did not have a lot of mass.” A second student agreed and added, “The wax sank in beaker B because it had more mass than the candle in beaker A.” These answers typified students’ responses.

Ms. Bell then asked the students to predict what would happen if the pieces of wax were switched. Students predicted that the small candle would float in beaker B because they said, “It doesn’t gain density by switching beakers and “It has the same amount of mass.” Likewise, they predicted that the large piece of wax would sink in beaker A because they said, “It too had the same amount of mass and the large piece will not lose density from switching beakers.” The students neglected the nonobvious role of the liquids in the situation, a tendency that fits with a linear pattern of reasoning about sinking and floating. Ms. Bell then switched the pieces of wax into opposite beakers and the students observed that the small piece of wax sank and the large piece floated.

The outcome was discrepant with what most of the students expected. The class discussed their predictions in comparison to the surprising results they observed. One student commented, “I didn’t know that the liquid can affect how something floats or sinks.” Another student noted, “I was so focused on the pieces of wax that I forgot about the liquids.”

By making the nonobvious relationship of the fluid obvious through this demonstration, students recognized that the causal agent involved in sinking and floating is the relationship between two densities (which are themselves relationships). By reasoning relationally as opposed to linearly, about what happens when something sinks and floats, the students achieved a deeper understanding of the variables involved in sinking and floating and subsequently were more successful at predicting whether an object would sink or float in a given fluid.

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[1] This example outlines research conducted in schools by Carolyn Houghton and Belinda Bell as part of The Understandings of Consequence Project.

[2] This activity is adapted from an activity called “The Funny Water” written by Tik L. Lien. It can be found in Lien, T. L. (1987). *Invitations to science inquiry: Second ed.* Chino Hills, CA: Science Inquiry Enterprises.

Sample of an Explanation Sheet to Help Students Understand Relational Causality and Lift

In order to help students adopt a causal model that will help them understand scientific phenomena more deeply, as part of the Understandings of Consequence Project we have attempted to change the expectations that they bring to learning a new topic at the outset. For instance, when learning about lift, students were encouraged to think of the cause of lift as located in the context of a relationship. Here is an example of a sheet that we gave to students to encourage them to view causality relationally when thinking about lift.

Relational Causal Stories

Sometimes we need to think about what is happening in a relational way. A *relational causal story* explains what is going on.

Lift is best described by a <u>relational causal story</u>. Lift is due to the difference in the air pressure at the top and at the bottom of the airplane wing. Airplane wing surfaces are curved on top as pictured in Figure 1. So when the wings move through the air, the air along the top has farther to travel to get from the front edge of the wing to the back edge than the air moving across the flat surface on the bottom. Therefore the air must move more quickly over the top surface. Air exerts pressure on everything, but faster moving air exerts less pressure than slower moving air. (This is called Bernoulli's principle.) See Figure 2. Therefore, the cause of lift is the relationship between the air pressure on the top and bottom of the wing due to the speed of the air moving across each.

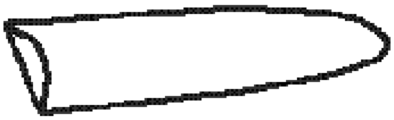

Figure 1. Airplane wing

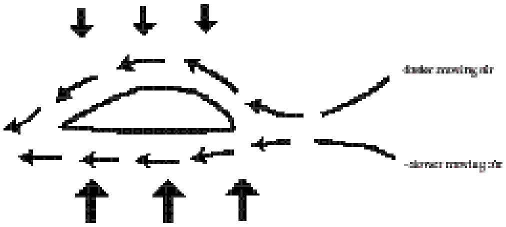

Figure 2. Cross section (slice) of airplane wing

If the air pressures on the top and the bottom of the wing are equal, then the air pushes equally on the top and the bottom of the wing and there is no lift. If the air pushes more on the bottom than on the top, the wing lifts up. What do you think might happen if the curved surface were on the bottom of the wing and the flat surface on the top? The outcome depends on relationship of the air pressure on the top of the wing to the air pressure on the bottom, so you need to look for the cause of the outcome in the relationship between the two.

In a relational causal story:

- The outcome is caused by the relationship between two or more elements of the system.
- Neither element is the cause by itself.
- If you focus on only one of the elements that contributes to the outcome, you lose important parts of the story.