Journal of Elementary Science Education, Vol. 20, No. 4 (Fall 2008), pp. 1-14.

ASTE Invited Article

What Can Developmental Theory Contribute to Elementary Science Instruction?

Anton E. Lawson, Arizona State University

This material is based upon research partially supported by the National Science Foundation under award No. EHR 0412537. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author and do not necessarily reflect the views of the National Science Foundation.

Abstract

Children personally construct explanations of natural phenomena, some of which differ from currently accepted scientific explanations. The replacement of personal explanations with scientific explanations, as well as the development of concrete, formal, and post-formal reasoning patterns, requires self-regulation in which alternative explanations are generated and tested in a hypothetico-predictive fashion. Consequently, inquiry-based science instruction in which students explore nature; encounter puzzling observations; and, subsequently, generate and test their own explanations not only helps them acquire meaningful concepts, it also helps them develop intellectually and become scientifically literate.

Introduction

One evening as my six-year-old daughter and I were driving to the store to buy some ice cream, she looked to the east and noticed that the moon had just risen above the horizon. After watching for a few seconds, she exclaimed, “Look, Dad, the moon is following us.” I looked over, and sure enough, the moon certainly seemed to be following right along as we headed north.

Of course, I knew otherwise. The moon just appeared to be following us in part because it appeared large, thus relatively near. I also knew that convincing my daughter that the moon really wasn’t following us would be fruitless. So I asked her, “What do you think would happen if we turned around and drove in the opposite direction? Do you think the moon would follow us south?” To which she replied, “Sure.” So we turned around and headed south. Sure enough, the moon appeared to follow us south just as though it were on a leash. This observation clearly supported my daughter’s misconception about the moon’s behavior. I then asked her if she thought the moon was also following the cars that were headed in the opposite direction, to which she unhesitatingly replied, “Yes.”

A few years later, while again driving north on the same street, we encountered the same phenomenon. When I reminded my daughter of her previous view that the moon was following us, she sheepishly admitted that although she had once believed this, she now knew better. When I asked her why she changed her mind, she was at a loss as to what to say.[1]

This example demonstrates two counterintuitive facts. First, although we tend to believe that our senses give us reliable information, they are often misleading. Second, overcoming misleading perceptions and the frequently resulting misconceptions generally requires more than simply telling children the right answers. Instead, according to developmental theory, real understanding (as opposed to rote learning) requires active participation in an internally driven and self-guided process called self-regulation—sometimes called *equilibration* (e.g., Grossberg, 1982; Kosslyn & Koenig, 1995; Levine & Prueitt, 1989; Piaget, 1985).

This article will argue that the best way to teach science so that students understand important science concepts is to provoke them to undergo self-regulation. Importantly, doing so results not only in conceptual understanding, it also results in the development of creative and critical reasoning skills—skills necessary for informed decisionmaking, problem solving, and general scientific literacy. Consequently, we need to learn more about self-regulation and how teachers can provoke its use in the classroom.

What Is the Pattern of Self-Regulation?

Although my daughter was not able to reconstruct the steps taken during her self-regulation and eventual conceptual change, let's consider an example in which we can reconstruct the steps—one in which I was the one undergoing self-regulation. Reconstructing the steps should give us a better understanding of the process and what teachers can do to help students understand concepts and continue developing intellectually.

Before I arrived home one evening, my wife had lit the gas grill and put some meat on to cook. Upon arriving, she asked me to check the meat. While doing so, I noticed that the grill was no longer lit. It was windy, so I figured the wind had blown out the flames as it had a few times before. I tried to relight the grill by striking a match and inserting it into a small hole just above one of the unlit burners, but the grill did not relight. I tried a second, and then a third match, but it still did not relight. At this point, I suspected that the tank might be out of gas, so I lifted the tank and, sure enough, it lifted easily as though it was empty. I then checked the lever-like gas gauge and found it pointing at empty. So it seemed that the grill was no longer lit, not because the wind had blown out the flames but because its tank was out of gas.

What reasoning pattern was guiding this self-regulated learning? Retrospectively, it would seem that my reasoning, like my daughter's thinking about the moon, was initiated by a puzzling observation. In this case, the grill was no longer lit. In response to this puzzling observation, the reconstructed reasoning, along with its labeled elements, seems to have gone like this:

If . . . the wind had blown out the flames (spontaneously generated wind explanation),
and . . . a match is used to relight the grill (imagined test),
then . . . it should relight (expected result),
but . . . when the first match was tried, the grill did not relight (observed result).
Therefore . . . either the wind explanation is wrong or something is wrong with the test. Perhaps the match flame went out before it could ignite the escaping

gas. This seems plausible because the wind had blown out several matches in the past. So retain the wind explanation and try again (conclusion).

Thus,

If . . . the wind had blown out the flames (wind explanation),
and . . . a second match is used to relight the grill (imagined test),
then . . . it should relight (expected result),
but . . . when the second match was used, the grill still did not relight (observed result).
Therefore . . . once again, either the wind explanation is wrong or something is wrong with the test (conclusion). Although it appeared as though the inserted match flame reached the unlit burner, perhaps it nevertheless did get blown out. So, again, retain the wind explanation and repeat the experiment, but, this time, closely watch the match flame to see if it does in fact reach its destination.

Thus,

If . . . the wind had blown out the flames (wind explanation),
and . . . a third match is used to relight the grill while closely watching the flame (imagined test),
then . . . the flame should reach its destination and grill should relight (expected result),
but . . . although the flame appeared to reach its destination, the grill still did not relight (observed result).
Therefore . . . apparently there was nothing wrong with the test. Instead, the wind explanation is probably wrong and another explanation is needed (conclusion). Perhaps the tank is out of gas.

Thus,

If . . . the tank is out of gas (empty-tank explanation),
and . . . the tank is lifted (imagined test),
then . . . it should feel light and lift easily (expected result),
and . . . when the tank was lifted, it felt light and lifted easily (observed result).
Therefore . . . the empty-tank explanation is supported (conclusion).

Further,

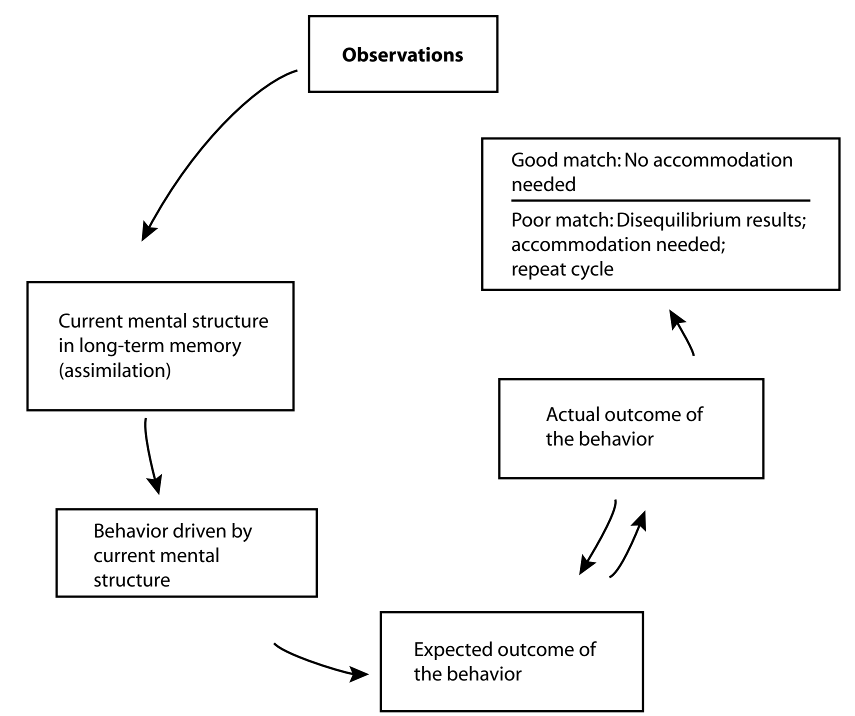
If . . . the tank is out of gas (empty-tank explanation),
and . . . the gas gauge is checked (imagined test),
then . . . it should be pointed at empty (expected result),
and . . . it was pointed at empty (observed result).
Therefore . . . the empty-tank explanation is supported once again (conclusion).

The above *If/and/then/Therefore* pattern that apparently guided my reasoning and learning can be characterized as hypothetico-predictive (HP) (or hypothetico-deductive) in that a puzzling observation prompted the spontaneous generation of possible explanations (i.e., hypotheses), which were then tested by deducing expected results (i.e., predictions) from the hypotheses and their imagined/

planned tests and then by comparing predicted and observed results. Thus, we can see that self-regulation involves generating and testing hypotheses in an HP fashion. Sometimes, it results in the rejection of misconceptions. Other times, it simply results in the sorting out of several possible explanations to arrive at the one most consistent with the available evidence.

Figure 1 models the HP nature of the process, including its dual aspects of assimilation and accommodation. First, the initial observation of the unlit grill was immediately assimilated by a "wind mental structure," which was present in long-term associative memory. Thus, upon seeing that the flames were out, the hypothesis that the wind had blown them out was immediately generated. This assimilation soon led to disequilibrium when the wind hypothesis was initially tested and contradicted. Disequilibrium grew when subsequent observations also did not match expectations drawn from the wind hypothesis (i.e., the grill still did not relight with a second and a third match). Disequilibrium did not last long, however. After rejecting the wind hypothesis, an alternative empty-tank hypothesis, which represents an attempt at accommodation in light of the contradictory evidence, was generated. The subsequent test and support of the empty-tank hypothesis allowed assimilation of all of the observations. Thus, disequilibrium was eliminated and equilibrium was restored.

Figure 1. What Steps Are Involved in Learning?



Note: Self-regulation, or equilibration, begins with spontaneous assimilation. The mismatch of expected and observed outcomes causes disequilibrium and the need for accommodation.

As mentioned, when children engage in self-regulated learning, they not only learn new facts and concepts (sometimes referred to as *declarative knowledge*), they also become better at learning as their creative and critical reasoning skills (sometimes referred to as *procedural knowledge*) develop. This implies that when science (or any subject for that matter) is taught in ways that encourage students to inquire, encounter puzzling observations, and subsequently generate and test their own ideas, they are not only getting help acquiring meaningful (non-rote) declarative knowledge, they are also getting help developing their reasoning skills. In perhaps more familiar terms, they are not simply getting a fish, they are getting taught how to fish.

The next section will consider the general path of intellectual development so that we can begin to understand how to match classroom inquiries with students' developmental capabilities. To press the analogy a bit further, our budding fishermen need to be successful. Hence, they need to learn how to catch small fish before they can hope to land the big ones. In terms of science concepts, understanding the observable and familiar must come before tackling the abstract and unfamiliar.

What Is the General Path of Intellectual Development?

Children appear capable of a rudimentary form of HP reasoning virtually at birth. We can be fairly certain of this because the pattern can be found in nonhumans. For example, Hauser (2000) conducted a revealing experiment with rhesus monkeys. First, a monkey was shown an eggplant—a favorite food item. In full view, the eggplant was then placed behind a screen. A second eggplant was then placed behind the screen. Then, when the screen was lifted, the length of time the monkey looked at the two revealed eggplants was measured, which turned out to be about one second. Next, the conditions were changed. In the initial changed condition, one eggplant was placed behind the screen followed by a second eggplant. Then, without the monkey knowing it, the second eggplant was removed. Now, when the screen was lifted, the monkey looked at the unexpected single remaining eggplant for about three to four seconds. The same increase in looking time occurred when a third eggplant was secretly added and then revealed.

Thus, the monkey had a clear expectation of seeing two eggplants and when either one or three eggplants unexpectedly showed up, the monkey was puzzled as evidenced by the increase in looking time. In the first unexpected condition, the monkey's "reasoning" can be summarized like this:

If . . . one eggplant is placed behind the screen,
and . . . another is added,
then . . . there should be two eggplants behind the screen,
but . . . there is only one eggplant.
Therefore . . . I am puzzled and need to look at the puzzling situation longer.

If we assume that this pattern of HP reasoning in humans is present at birth, then the general path of intellectual development involves a growing awareness (i.e., consciousness) of one's reasoning patterns as well as increases in the contexts to which the patterns can be applied. Let's see how this might work in terms of Piaget's well-known concrete and formal operational stages (e.g., Inhelder & Piaget, 1958; Piaget & Inhelder, 1969) as well as a possible post-formal stage

(Lawson, Clark, Cramer-Meldrum, Falconer, Kwon, & Sequist, 2000a; Lawson, Drake, Johnson, Kwon, & Scarpone, 2000b).

The Concrete Operational Stage (Seven Years Old to Early Adolescence)

Beginning at age 7, the prior acquisition of language to name objects, events, and situations during the preoperational stage (generally ages 2 to 7 years) allows the child to apply HP reasoning to a new level: the level of ordering and classifying (i.e., creating variables and higher-order categories of objects, events, and situations). The observable and named objects, such as tables and dogs, of the preoperational stage become the categories, such as furniture and animals, of the concrete stage. For example, to test the claim that concrete operational children can generate HP arguments to test descriptive hypotheses, a series of classification tasks, including the Mellinark Task (see Figure 2) were administered to children ranging in age from 6 to 14 years (Lawson, 1993). Brief one-on-one instruction was then used to teach them how to discover the relevant features using HP arguments such as the following example:

If . . . tiny spots make a creature a Mellinark (descriptive hypothesis),
and . . . I look at all of the non-Mellinarks in row 2,
then . . . none of them should have tiny spots,
but . . . some do have tiny spots.
Therefore . . . tiny spots are not the key feature or at least not the only key feature.

Further,

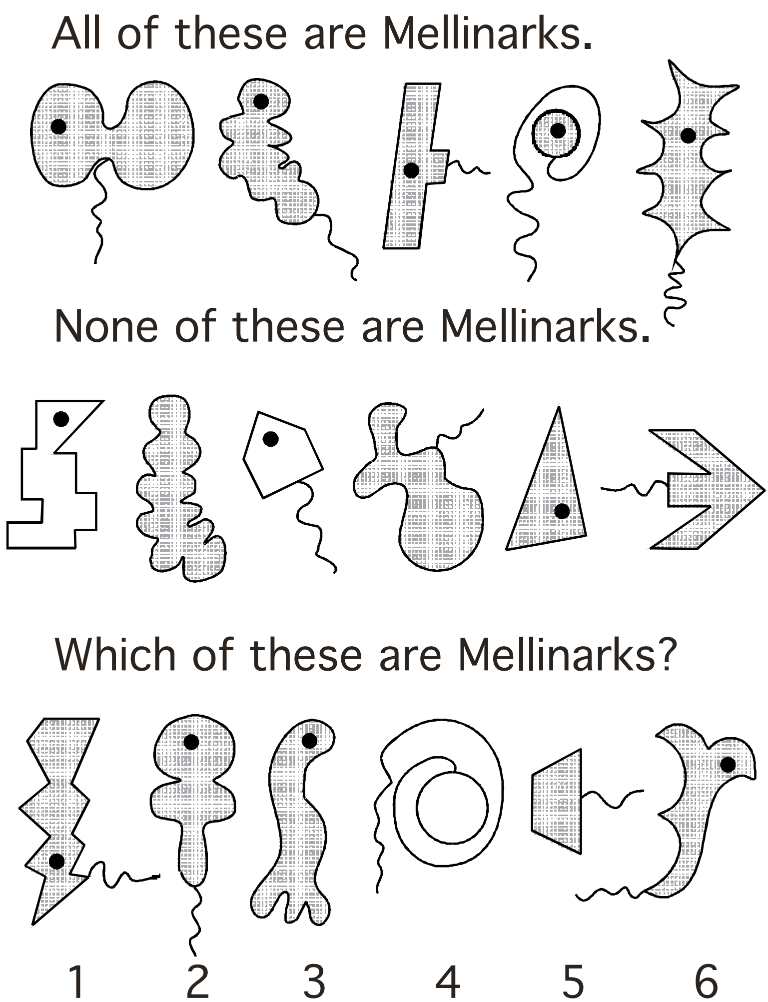
If . . . tiny spots, a tail, and a big dot together make a creature a Mellinark (descriptive hypothesis),
and . . . I look at all of the Mellinarks in row 1,
then . . . all of them should have all three features,
a*nd* . . . all of them do have all three features.
Therefore . . . perhaps Mellinarks are creatures with tiny spots, a tail, and a big dot.

Still further,

If . . . tiny spots, a tail, and a big dot together make a creature a Mellinark,
and . . . I look at all of the non-Mellinarks in row 2,
then . . . none of them should have all three features,
a*nd* . . . none of them do have all three features.
Therefore . . . most likely Mellinarks are creatures with tiny spots, a tail, and a big dot.

Interestingly, none of the 6-year-olds could generate or comprehend this sort of argument and identify the Mellinarks in row 3 (i.e., creatures 1, 2, and 6), whereas half of the 7-year-olds could, as could virtually all of the 8- to 14-year-olds. Therefore, results supported the hypothesis that the concrete stage, which begins rather abruptly at 7 years of age (most likely related to a growth spurt of the frontal lobes), involves the ability to use HP reasoning to serial order and to categorize the objects, events, and situations in the child's environment—all mediated by language. In other words, at the concrete stage, children become able to generate and test descriptive hypotheses by observing the presence or absence of features such as spots, tails, and curvy sides.

Figure 2. The Mellinark Task



Source: Elementary Science Study (1974)

The Formal Operational Stage (Early to Late Adolescence)

Following a comprehensive review of the psychological literature, Moshman (1998) concluded the following:

> In fact, there is surprisingly strong support for Piaget's 1924 proposal that formal or *hypothetico-deductive reasoning*—deliberate deduction from

propositions consciously recognized as hypothetical—plays an important role in the thinking of adolescents and adults but is rarely seen much before the age of 11 or 12. (p. 972)

By hypothetical, Moshman (1998) is referring to explanatory as opposed to descriptive hypotheses. For example, consider the following question: "What causes pendulums to swing fast or slow?" To answer this causal question, one must generate and test alternative explanations, not descriptions (cf., Inhelder & Piaget, 1958, Chapter 4). For example:

If . . . changes in swing speeds are caused by the amount of weight hanging on the end (weight explanation),
and . . . the weight is varied while holding other possible causes constant,
then . . . the swing speed should vary,
but . . . the swing speed does not vary.
Therefore . . . the weight explanation is not supported.

This reasoning pattern is the same as that used to test descriptive hypotheses during the prior concrete stage. Thus, the difference between formal and concrete reasoning is not the HP pattern. Again, the difference appears to be the context in which the pattern can be applied. Concrete reasoning is about testing descriptive hypotheses, while formal reasoning is about testing causal hypotheses.

The Post-Formal or "Theoretical" Stage (Late Adolescence and Adulthood)

You may recall Louis Pasteur's famous test of spontaneous generation and biogenesis theories (see, for example, Dubos & Brock, 1998). The HP argument summarizing his test is as follows:

If . . . a special vital force enters nonliving matter to bring it to life (spontaneous generation theory),
and . . . an open swan-necked flask with gravy is boiled for an hour to kill any microbes (planned test),
then . . . after several days, living microbes should be observed growing in the flask (prediction). Living microbes should be observed because the vital force should be able to pass through the open neck, enter the gravy, and bring it to life (theoretical rationale).

Alternatively,

If . . . the vital force does not exist and new life comes only from prior life (alternative biogenesis theory),
then . . . living microbes should not be observed in the flask (prediction). This alternative prediction follows because spores drifting in the air cannot fall into the flask due to the downward curve in its neck. Further, living microbes can survive a short period of heating but not an hour of boiling (theoretical rationale).

Although it is identical to the prior reasoning in form, this argument differs from formal stage arguments in at least two important ways. Here, the proposed cause is unseen (i.e., theoretical) whereas at the formal stage, the proposed cause (weight) was amenable to sensory experience. Unlike formal reasoning wherein the proposed cause and the independent variable of the experiment designed to test it were the same (i.e., to test the weight hypothesis we varied the amount of weight hung on the string's end), this is no longer the case. In Pasteur's experiment, the independent variable is the presence or absence of a downward curve in the neck of his flasks, while the proposed cause is an unseen vital force or unseen drifting spores (see Dubos & Brock, 1998). Since the proposed cause and the independent variable are not the same, a theoretical rationale is needed to link the two so that a reasonable test can be conducted. For these reasons, such "post-formal" reasoning is more abstract and complex than formal reasoning (e.g., Lawson et al., 2000a, 2000b) and is apparently not fully achieved until late adolescence after a final brain growth spurt at age 18 (Thatcher, 1991; Thatcher, Walker, & Giudice, 1987). A clear implication is that theoretical concepts should not be introduced during the elementary grades—at least not if you want your students to understand why we believe in some (e.g., biogenesis) and not others (e.g., spontaneous generation).

How Does Intellectual Development Occur?

In theory, self-regulation provokes intellectual development when one "internalizes" both its products and its procedures. According to Piaget (1976), internalization occurs due to a process called *reflective abstraction*. Reflective abstraction occurs when contradictory feedback and the resulting disequilibrium prompt individuals to reflect on their own thinking and the thinking of others. The result is that individuals become more aware of, more conscious of, and more skilled in use of the procedures used in gaining declarative knowledge.

Relatively recent neurological research indicates that, once acquired, procedural knowledge structures reside in neural networks that are hierarchical in nature. Interestingly, the hierarchical networks appear to culminate in single neurons located in the brain's prefrontal cortex (Wallis, Anderson, & Miller, 2001). Alternatively, declarative knowledge structures reside in associative memory, which is located primarily in the hippocampus, the limbic thalamus, and the basal forebrain (Kosslyn & Koenig, 1995).

Interestingly, people generally know if and when they learned a specific piece of declarative knowledge; however, they seldom know if and when their more elusive and less easily characterized procedural knowledge structures developed. This means that people who lack higher-order reasoning abilities do not realize their deficiencies, while people who have developed such reasoning abilities often assume incorrectly that everyone else has developed them as well. Not surprisingly, a number of problems result, not the least is that many science teachers ignore procedural knowledge and focus solely on teaching and testing declarative knowledge. Unfortunately, because the pace of intellectual development lags in so many students, a huge portion of what we try to teach elementary and secondary students (and even many college students) is missing the mark. Instead, it simply goes in one ear and out the other.

This view of intellectual development helps clarify why stage retardation occurs (i.e., why some students fail to develop intellectually beyond the concrete stage). Suppose, for example, two isolated islands existed years ago, each ruled by an all-powerful king. When questions arose, the islanders asked the king for answers—answers that were accepted as true. One day, a foreign ship arrived at one of the islands. Over time, trading relationships were established between the island and several foreign countries. Importantly, not only did the ships bring new goods, the sailors also brought new ideas. The ideas spread throughout the island, some of which contradicted the "truths" previously handed down by the king. The islanders began wondering which ideas were true and, more importantly, how they could tell. Eventually, an upheaval took place in which the king was overthrown and replaced by a government run by the people. Decades later, an anthropologist arrived on the island to study its culture. As part of her study, she administered a reasoning test to the island's adults. Soon after, she discovered the other island. She was the first outsider to discover the island, which was still controlled by an all-powerful king. She administered the reasoning test to the adults on this island as well. Which population of islanders did better on the reasoning test? Clearly, the adults on the first island should be better. Piaget (1962) pointed out the reason as early as 1928 when he stated that the development of reasoning occurs as a consequence of "the shock of our thoughts coming into contact with others, which produces doubt and the desire to prove" (p. 204). Piaget went on to state that

> The social need to share the thought of others and to communicate our own with success is at the root of our need for verification. . . . [A]rgument is, therefore, the backbone of verification. Logical reasoning is an argument which we have with ourselves, and which produces internally the features of a real argument. (p. 204)

In other words, the growing awareness of and ability to use internalized arguments to guide one's reasoning occurs as a consequence of arguments with others in which alternative ideas are generated and accepted or rejected as the basis of evidence and reason as opposed to authority or emotion. If alternative ideas do not exist, then no external arguments ensue, and no internalization of patterns of argumentation results.

What Can Teachers Do?

Given that many students fail to develop formal and/or post-formal reasoning patterns and that their reasoning deficiencies lead to difficulties in rejecting misconceptions, problem solving, understanding science concepts, and understanding the nature of science, more emphasis on teaching students to reason effectively is urged. Effective reasoning lies at the heart of scientific literacy, so the key pedagogical question is, "What can teachers do to encourage intellectual development?"

As mentioned, the answer is to teach in ways that encourage students to inquire. Thus, the most appropriate way—perhaps the only way to accomplish this objective—is to teach in ways that encourage students to explore nature; reveal their prior conceptions; and test them in an atmosphere in which ideas are openly proposed, debated, and tested, with the means of testing becoming an explicit focus of classroom attention. This so-called "inquiry method" of instruction (sometimes called *learning cycle* instruction; see Marek, 2008) enables this to happen. To end on a more practical note, a list of the procedural skills that elementary and secondary school teachers should help children and adolescents develop using inquiry instruction appears in Table 1.

Table 1. Creative and Critical Reasoning Skills

Accurately Describing Nature
- Describing, seriating, and classifying objects in terms of observable characteristics (K-3)
- Describing, seriating, classifying, and measuring objects in terms of variables such as amount, length, area, weight (K-6), volume, and density (6-9)
- Identifying continuous and discontinuous variables and naming specific values of those variables (K-9)
- Measuring, recording, and graphing the frequency of occurrence of certain values of characteristics in a sample of objects (4-6)
- Determining the average, median, and modal values in a frequency distribution (7-9)
- Recognizing the difference between a sample and a population, and identifying ways of obtaining random (unbiased) samples (7-9)
- Estimating the probability of occurrence of specific population characteristics based on the frequency of occurrence of those characteristics in random samples (7-9)

Raising and Stating Causal Questions
- Distinguishing between descriptive and causal questions (K-6)
- Stating causal questions based on puzzling observations (K-3) and on paragraphs and articles (4-9)
- Distinguishing between observations and causal questions (K-3)
- Recognizing causal questions even when stated in expository form rather than in interrogatory form (4-9)
- Distinguishing between causal questions and proposed explanations (i.e., causal hypotheses and theories) even when the proposed explanations are presented in interrogatory form (7-12)

Proposing Alternative Explanations
- Distinguishing between descriptions and explanations (K-6)
- Distinguishing between explanations and terms used to label phenomena (4-9)
- Systematically generating combinations of proposed explanations (7-12)

Planning and Conducting Tests of Proposed Explanations
- Recognizing the need to test a proposed explanation prior to drawing a conclusion about its relative truth or falsity (K-12)
- Selecting reasonable explanations to test (K-12)
- Distinguishing among tests requiring the collection of circumstantial, correlational, and experimental evidence (9-12)
- Deducing and stating reasonable expectations (i.e., predictions) based on the assumed truth of proposed explanations and their planned tests (K-12)
- Distinguishing between proposed explanations and expectations (4-12)
- Distinguishing between controlled and uncontrolled experiments (4-9)
- Planning experiments in which only one independent variable varies (4-9)
- Recognizing independent, dependent, and controlled variables in experiments (4-9)
- Recognizing faulty experimental designs when
  - The design cannot test the proposed explanation (4-12)
  - The method of data collection is unreliable (4-12)
  - Proper controls are not included (4-9)
  - The amount of data is insufficient (9-12)

Table 1 (cont.)

Collecting, Organizing, and Analyzing Evidence
- Recognizing measurement errors (4-9)
- Recognizing when the precision of measurement is warranted (9-12)
- Constructing tables and frequency graphs (4-9)
- Measuring, recording, and graphing the values of two variables on a graph (7-12)
- Constructing a contingency table of discontinuous variables (7-12)
- Recognizing elements in common to several items of data (4-12)
- Recognizing prevailing trends in data and extrapolating and interpolating (7-12)
- Applying quantitative notions of probability, proportion, percentage, and correlation to natural phenomena and recognizing when variables are related additively or multiplicatively, setting up simple quantitative equations to describe these relationships (7-12)
- Recognizing direct, inverse, or no relationship between variables (4-9)
- Recognizing that when two things vary together, the relationship may be coincidental, not causal (7-12)
- Recognizing additional evidence needed to establish cause and effect (7-12)

Drawing and Applying Conclusions
- Evaluating the relevancy of data and drawing conclusions by comparing observed and expected results
- Distinguishing between observed results (i.e., evidence/data) and conclusions (4-9)
- Distinguishing among circumstantial, correlational, and experimental evidence (4-9)
- Recognizing when data are unrelated to the tested explanation (4-9)
- Recognizing data that support a tested explanation (4-9)
- Recognizing data that do not support a tested explanation (4-9)
- Combining both supportive and nonsupportive evidence from a variety of sources to weigh the likely truth or falsity of tested explanations (10-12)
- Postponing judgment if insufficient evidence exists (4-12)
- Recognizing the distinction (4-9)
- Recognizing the tentativeness inherent in all scientific conclusions (10-12)

Note: Grades in which skills should be emphasized follow the statements.

Endnote

[1] My daughter's initial observation-based view that the rising moon follows cars as they travel north or south is, in many ways, similar to the ancients' view that the sun orbits the Earth. Of course, scientists have known better for several centuries. Instead, each day the Earth makes one complete rotation from west to east at an equatorial speed of some 1,038 miles per hour, the sun stands virtually motionless. Try convincing a young child—or an ancient Greek—that this is so given that (1) they can clearly see that the sun passes overhead each day from east to west, (2) the Earth certainly feels stationary, (3) we do not encounter constant gale-force easterlies, and (4) Olympic broad jumpers do not land in the stands well to the west of their jumping-off points. Given this evidence, perhaps we should not be too surprised to learn that one-in-five American adults still believe that the sun orbits the Earth (Dean, 2005). By the way, if you believe that a rotating Earth orbits the sun, why do you believe this as opposed to the more intuitively appealing counterview? Is it because you understand the scientists' reasoning and evidence or is it simply because you have blindly accepted their conclusions? If the reason is the latter, what does this imply about the way you learned science and the way science should be taught?

References

Dean, C. (2005, August 30). Scientific savvy? In U.S., not much. *The New York Times*. Retrieved September 17, 2008, from www.nytimes.com/2005/08/30/science/30profile.html.

Dubos, R. J., & Brock, T. D. (1998). *Pasteur and modern science*. Washington, DC: American Society of Microbiology.

Elementary Science Study. (1974). *Attribute games and problems*. New York: McGraw-Hill.

Grossberg, S. (1982). *Studies of mind and brain.* Dordrecht, Holland: D. Reidel.

Hauser, M. D. (2000). What do animals think about numbers? *American Scientist, 88*, 144-151.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. New York: Basic Books.

Kosslyn, S. M., & Koenig, O. (1995). *Wet mind: The new cognitive neuroscience.* New York: The Free Press.

Lawson, A. E. (1993). Deductive reasoning, brain maturation, and science concept acquisition: Are they linked? *Journal of Research in Science Teaching, 30*, 1029-1052.

Lawson, A. E., Clark, B., Cramer-Meldrum, E., Falconer, K. A., Kwon, Y-J., & Sequist, J. M. (2000a). The development of reasoning skills in college biology: Do two levels of general hypothesis-testing skills exist? *Journal of Research in Science Teaching, 37*, 81-101.

Lawson, A. E., Drake, N., Johnson, J., Kwon, Y-J., & Scarpone, C. (2000b). How good are students at testing alternative explanations of unseen entities? *The American Biology Teacher, 62*, 249-255.

Levine, D. S., & Prueitt, P. S. (1989). Modeling some effects of frontal lobe damage: Novelty and perseveration. *Neural Networks, 2*(2), 103-116.

Marek, E. (2008). Why the learning cycle? *Journal of Elementary Science Education, 20*(3), 63-69.

Moshman, D. (1998). Cognitive development beyond childhood. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology. Vol. 2: Cognition, perception, and language* (5th ed.) (pp. 947-978). New York: Wiley.

Piaget, J. (1962). *Judgment and reasoning in the child.* London: Routledge & Kegan Paul. (Original work published 1928)

Piaget, J. (1976). *Piaget's theory*. In B. Inhelder & H. H. Chipman (Eds.), *Piaget and his school: A reader in developmental psychology* (pp. 11-23). New York: Springer-Verlag.

Piaget, J. (1985). *The equilibration of cognitive structures: The central problem of intellectual development* (T. Brown & K. J. Thampy, Trans.). Chicago: The University of Chicago Press.

Piaget, J., & Inhelder, B. (1969). *The psychology of the child*. New York: Basic Books.

Thatcher, R. W. (1991). Maturation of the human frontal lobes: Physiological basis of staging. *Developmental Neuropsychology, 7*, 397-419.

Thatcher, R. W., Walker, R. A., & Giudice, S. (1987). Human cerebral hemispheres develop at different rates and ages. *Science, 236*, 1110-1113.

Wallis, J. D., Anderson, K. C., & Miller, E. K. (2001). Single neurons in prefrontal cortex encode abstract rules. *Nature, 411*, 953-956.

Correspondence regarding this article should be directed to

Anton E. Lawson
School of Life Sciences
Arizona State University
P.O. Box 875006
Tempe, AZ 85287-5006
(480) 965-2540
Fax: (480) 965-6869
Anton.lawson@asu.edu

Invited manuscript.