CHAPTER 9

Children as Scientific Thinkers

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Children are engaged in scientific thinking when they attempt to understand and explain entities and processes in the natural world. One type of scientific thinking involves thinking about the *content* of science. The other type involves the process of *doing* science.

THINKING ABOUT THE CONTENT OF SCIENCE

Scientific content includes a very large set of specific domains, traditionally arranged by professional organizations, university departments, text book publishers, and state curriculum designers into categories such as physics, chemistry, biology, and earth sciences (e.g., the alphabetical listing of the National Academy of Sciences' 31 divisions ranges from "Animal, Nutritional, and Applied Microbial Sciences" and "Anthropology," to "Social and Political Science" and "Systems Neuroscience"). Moreover, each of these broad domains of science has many subdivisions (both in university organizational structures and the table of contents of science text books).

The continually expanding range of such substantive topics in science is daunting. By some estimates, there are thousands of possible science concepts that could be taught (Roth, 2008) and the science standards proposed by each of the 50 states in the United States often run to hundreds of pages, and a typical middle-school textbook in a broad topic like biology or earth science can run to 700 or 800 pages. Consequently, science educators have lamented the fact that the K-12 science curriculum is "a mile wide and an inch deep." One proposed remedy to this problem is to eschew topical breadth and instead focus on depth, a strategy that appears to be effective at improving long-term learning in science (Schwartz, Sadler, Sonnert, & Tai, 2008).

Of course, when children first begin to think about the content of science, they are not influenced, for better or worse, by the kinds of categories listed above. Instead, they simply notice and wonder about clouds, bugs, bubbles, food, people, dreams, and an endless array of other entities that they encounter in their world. For example, our own research on children's scientific curiosity (Jirout, 2011) has recorded questions from 4- and 5-year-old children such as "Can bees be killed by electricity?, "Do clouds make wind?", "How do leaves change their colors?", and "What do worms' eyes look like?" Research on children's thinking about science content ranges from studies of infants' understanding of causality and simple physical regularities (Baillargeon, 2004; Gopnik, Meltzoff, & Kuhl, 1999), to young children reasoning about the sun–moon–earth system (Vosniadou & Brewer, 1992), to college students reasoning about chemical equilibrium (Davenport, Yaron, Klahr, & Koedinger, 2008). These studies reveal a protracted period during which children often develop deeply entrenched misconceptions and preconceptions. In many cases children's developing understanding of the natural world recapitulates the history of scientific discovery, and in other cases, children's misconceptions turn out to be remarkably resistant to instruction (see "Problem-Solving Methods" section).

THINKING ABOUT THE PROCESS OF SCIENCE

The second kind of scientific thinking—*doing* science—includes a set of reasoning processes that can be organized into three broad, but relatively distinct, categories: formulation of hypotheses, design of experiments and observations, and evaluation of evidence. In turn, both the formation of hypotheses and the design and execution of experiments and observations can be viewed as types of problem solving, involving search in problem spaces (Newell & Simon, 1972). Scientific reasoning, under this view, consists of the coordination of this "dual search" in the experiment space and the hypothesis space (Klahr, 2000; Klahr & Simon, 1999; Klahr, Dunbar, & Fay, 1990). However, as in the case of thinking about the content of science, when children are engaged in these different aspects of the process of science, they are unaware of the distinctions between, for example, forming hypotheses and designing experiments, even though these distinctions are useful for psychologists who investigate the properties of these different aspects of scientific thinking.

The characterization of scientific reasoning as a kind of general problem solving raises the question about whether scientific thinking is qualitatively different from other types of reasoning. We believe that the answer is "no." That is, we will argue that the reasoning processes used in scientific thinking are not unique to scientific thinking: they are the very same processes involved in everyday thinking, so that questions about children's ability to think scientifically are inexorably linked to broad and general questions about cognitive development. Before turning to a summary of the relevant literature, it is worth noting that we are in good company in basing our review on the "nothing special" claim about the nature of scientific reasoning.

> The scientific way of forming concepts differs from that which we use in our daily life, not basically, but merely in the more precise definition of concepts and conclusions; more painstaking and systematic choice of experimental material, and greater logical economy. (Einstein, 1950, p. 98)

Nearly 40 years after Einstein's remarkably insightful statement, Francis Crick offered a similar perspective: that great discoveries in science result from commonplace mental processes, rather than from extraordinary ones. The greatness of the discovery lies in the thing discovered.

> I think what needs to be emphasized about the discovery of the double helix is that the path to it was, scientifically speaking, fairly commonplace. What was important was *not the way it was discovered*, but the object discovered—the structure of DNA itself. (Crick, 1988, p. 67; emphasis added)

The assumption in this chapter is that the literature on cognitive development can contribute to our understanding of children's scientific thinking because scientific thinking involves the same general cognitive processes—such as induction, deduction, analogy, problem solving, and causal reasoning—that children apply in nonscientific domains. Thus we get a window into children's *scientific* thinking by a better understanding of their thinking in more general terms. This view is simply a developmental version of Herbert Simon's insight about the psychology of scientific discovery:

> It is understandable, if ironic, that 'normal' science fits... the description of expert problem solving, while 'revolutionary' science fits the description of problem solving by novices. It is understandable because scientific activity, particularly at the revolutionary end of the continuum, is concerned with the discovery of new truths, not with the application of truths that are already well-known... it is basically a journey into unmapped terrain. Consequently, it is mainly characterized, as is novice problem solving, by trial-and-error search. The search may be highly selective—but it reaches its goal only after many halts, turnings, and back-trackings. (Simon, Langley, & Bradshaw, 1981, p. 5)

Perhaps this view overstates the case for all revolutionary discoveries (see e.g., Holton, 2003 on how Einstein's development of relativity departed from Simon's account of revolutionary ideas in science). Nevertheless, Simon's view remains an interesting and important characterization of discovery in the absence of a well-developed scientific schema.

SCIENTIFIC THINKING IN CHILDREN

General Overview of Research on Children's Scientific Thinking

A recent expert panel report from the National Research Council (NRC) (Duschl, Schweingruber, & Shouse, 2007), summarizes the research literature on children's scientific thinking from kindergarten to 8th grade. The report notes that young children have substantial knowledge of the natural world, much of which is implicit, and that scientific knowledge at any particular age is the result of a complex interplay among maturation, experience, and instruction. Moreover, general knowledge and experience play a critical role in children's science learning, influencing several key processes associated with science:

a. Knowing, using, and interpreting scientific explanations of the natural world
b. Generating and evaluating scientific evidence and explanations
c. Understanding how scientific knowledge is developed in the scientific community
d. Participating in scientific practices and discourse

Our emphasis in this chapter will be on the cognitive psychology end of the spectrum (items a through c), while acknowledging other aspects of "scientific practice" and "scientific discourse" that are important but not discussed much in this chapter.

Over the past half century, there has been a wealth of research in cognitive development on the processes and content of children's scientific thinking. While early theories of children's thinking characterized children as egocentric, perception-bound, and developing in relatively distinct stages (e.g., Piaget's theory), more recent theories have stressed children's development as a continuous process, with an emphasis on the ways in which children acquire new knowledge rather than on what they can and can't do at certain ages (e.g., Siegler's [1995] Overlapping Waves theory). One of the most pervasive findings in cognitive development research is that children have a large base of knowledge and abilities that are available from as early as the time children enter formal schooling, and this knowledge has a profound impact on what and how children subsequently learn when studying science.

From as early as infancy children begin to learn about the natural world in ways that will influence their later scientific thinking. Researchers have identified a number of distinct domains in which infants appear to develop specific knowledge, including psychology, biology, and physics. Another powerful achievement in the early years of life is the ability to think representationally—that is, being able to think of an object as both an object in and of itself as well as a representation of something else. Starting as early as three years, children are able to use scale models to guide their search for hidden objects in novel locations (DeLoache, 1987). This fundamental ability lies at the heart of important scientific skills such as analogical reasoning, and lays the ground-work for later scientific tasks such as interpreting and reasoning with models, maps, and diagrams.

The way in which this knowledge arises is a matter of fierce contention in cognitive development research. Some researchers have argued that children's knowledge acquisition is primarily "theory-based"—guided by top-down, domain-specific learning mechanisms for evolutionarily privileged domains (e.g., physics, biology, psychology, etc.)—while other researchers have argued that more attention-driven, domain-independent learning mechanisms are sufficient to account for the vast amount of information

that children acquire in the early years of life. These contrasting views are fueled in part by findings that, on the one hand, young children are capable of exhibiting adult-like performance in a variety of higher order reasoning tasks (Gelman & Coley, 1990; Gopnik & Sobel, 2000; Goswami & Brown, 1990; Keil, Smith, Simons, & Levin, 1998) while, on the other hand, children's performance on such tasks is often highly dependent on low-level perceptual, memory, and attentional factors (Fisher, Matlen, & Godwin, 2011; Rattermann & Gentner, 1998; Sloutsky, Kloos, & Fisher, 2007; Rakison & Lupyan, 2008; Smith, Jones, & Landau, 1996). Regardless of the cognitive mechanisms at play in the early years of life, however, it is clear that children have substantial knowledge about the physical world by the time they enter formal schooling. A major challenge in science education is to build on students' existing knowledge of the natural world to help them think and reason about the scientific phenomena.

Problem-Solving Methods

Given our view that scientific problem solving is a special case of general problem solving, we will summarize some key ideas about the psychology of problem solving. Newell and Simon (1972) define a problem as comprising of an initial state, a goal state, and a set of operators that allow the problem solver to transform the initial state into the goal state through a series of intermediate states. Operators have constraints that must be satisfied before they can be applied. The set of states, operators, and constraints is called a "problem space," and the problem-solving process can be characterized as a search for a path that links the initial state to the goal state.

In all but the most trivial problems, the problem solver is faced with a very large set of alternative states and operators, so the search process can be demanding. For example, if we represent the problem space as a branching tree of m moves with b branches at each move, then there are bm moves to consider in the full problem space. As soon as m and b get beyond very small values, exhaustive search for alternative states and operators is beyond human capacity, so effective problem solving depends in large part on how well the search is constrained. There are two broad categories—or methods—of search constraint: *strong methods* and *weak methods*. Strong methods are algorithmic procedures, such as those for long division or for computing means and standard deviations. The most important aspect of strong methods is that—by definition—they guarantee a solution to the problem they are designed to solve. However, strong methods have several disadvantages for human problem solvers. First, they may require extensive computational resources. For example, a strong method for minimizing cost (or maximizing protein) of a list of grocery items subject to other dietary and budget constraints is to apply a standard linear-programming algorithm. Of course, doing this in one's head while pushing a shopping cart is hardly feasible. Second, strong methods may be difficult to learn because they may require many detailed steps (e.g., the procedure for computing a correlation coefficient by hand). Finally, strong methods, by their very nature, tend to be domain specific and thus have little generality.

Weak methods are heuristic: they may work or they may not, but they are highly general. The trade-off for the lack of certainty associated with weak methods is that they make substantially lower computational demands, are more easily acquired, and are domain general. Of particular importance for this chapter is the possibility that some of the weak methods are innate, or, at the least, that they develop very early without any explicit instruction or training. Newell and Simon (1972) describe several kinds of weak methods, but here I will briefly describe only three.

Generate and Test

The generate and test method is commonly called "trial and error." Its process is simply applying some operator to the current state and then testing to determine whether the goal state has been reached. If it has, the problem is solved. If it has not, then some other operator is applied. In the most primitive generate and test methods, the evaluation function is binary: either the goal has been reached or it has not, and the next move does not depend on any properties of the discrepancy between the current state and the goal state or the operator that was just unsuccessfully applied. An example of a "dumb" generating process is searching in a box of keys for a key to fit a lock, and sampling with replacement: tossing failed keys back into the box without noting anything about the degree of fit, the type of key that seems to fit partially, and so forth. A slightly "smarter" generator would, at the least, sample from the key box without replacement.

Hill Climbing

The hill climbing method gets its name from the analogy of attempting to reach the top of a hill whose peak cannot be directly perceived (imagine a foggy day with severely limited visibility). One makes a tentative step in each of several directions, then heads off in the direction that has the steepest gradient. Hill climbing utilizes more information about the discrepancy between the current state and the goal state than does generate and test. Instead of a simple all-or-none evaluation, it computes a measure of goodness of fit between the two and uses that information to constrain search in the problem space.

Means–Ends Analysis

Perhaps the best-known weak method is means–ends analysis (Duncker, 1945; Newell & Simon, 1972). Means–ends analysis compares the current state with the goal state and notes the relevant differences. Then it searches for operators that can reduce those differences and selects the one that will reduce the most important differences and attempts to apply it to the current state. However, it may be that the operator cannot be immediately applied because the conditions for doing so are not met. Means–ends analysis then

formulates a sub-problem in which the goal is to reduce the difference between the current state and a state in which the desired operator can be applied, and then recursively attempts to solve the sub-problem.

An Empirical Study of Preschoolers' Problem-Solving Ability

With these brief descriptions of different problem-solving methods, we now turn to the question of the extent to which young children can actually employ them. In particular, we focus on the extent to which preschoolers can go beyond simple trial and error and use the much more powerful means–ends analysis method. In a study of preschool children's ability to "think ahead" while solving puzzles requiring means–ends analysis, Klahr and Robinson (1981) found that children showed rapid increases in their ability between the ages of 4 and 6 years. Children were presented with puzzles in which they had to describe a series of multiple moves... solving the problem "in their heads"... while describing the solution path. The main question of interest is how far into the future a child could "see" in describing move sequences. To avoid overestimating this capacity on the basis of a few fortuitous solutions, a very strict criterion was used: A child was scored as able to solve *n*-move problems only after proposing the minimum path solution for four different problems of length *n*. For example, to be classified as having the capacity to see five moves into the future, a child would have to produce the minimum path solution for four five-move problems.

The proportion of children in each age group producing correct solutions for all problems of a given length is shown in Figure 9.1. Note that the abscissa in the figure is not overall proportion correct, but rather a much

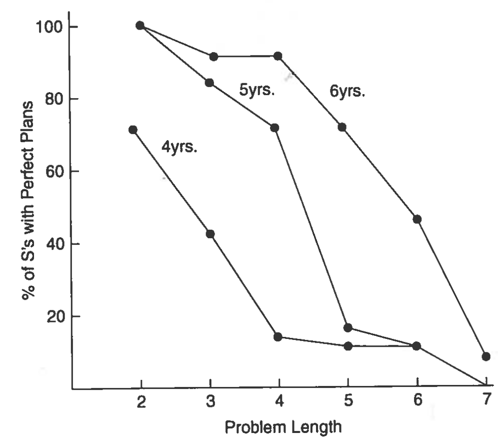

Figure 9.1 ***The proportion of children in each age group producing correct solutions for all Tower of Hanoi problems of a given length.***
Adapted from Klahr and Robinson (1981).

more severe measure: the proportion of children with perfect solutions on all problems of a given length. For example, 69% of the 6-year-olds were correct on all four of the five-move problems, while only 16% of the 5-year-olds and 11% of the 4-year-olds produced four flawless five-move solutions.

The absolute level of performance was striking: over two-thirds of the 5-year-olds and nearly all of the 6-year-olds consistently gave perfect four-move solutions, and over half of the 6-year-olds gave perfect six-move solutions. Almost half of the 4-year-olds could do the three-move problems. Note that these solutions required that the child manipulate mental representations of future states.

Children's and Adult's Problem Solving on a Scientific Reasoning Task

Klahr and Dunbar (1988) extended the search in a problem space approach and proposed that scientific thinking can be thought of as a search through two related spaces: an hypothesis space and an experiment space, with search in one of the spaces constraining and informing search in the other. Klahr, Fay, and Dunbar (1993) presented children (third and sixth graders) and adults with a complex scientific reasoning task in which they had to figure out the rules underlying the operation of a programmable toy robot. They discovered several important differences between the way that the children and adults approached the task.

(a) Children and adults respond differently to plausible and implausible hypotheses. One of the most robust findings in the literature on scientific reasoning in adults is that they attempt to confirm, rather than disconfirm, their hypotheses (Klayman & Ha, 1987). Similarly, developmental studies show that even when explicitly instructed to generate evidence that could potentially falsify a rule, children at the sixth-grade level or below perform very poorly (Kuhn, 1989; Ward & Overton, 1990). However, Klahr, Fay, and Dunbar (1993) report a more flexible kind of response: When hypotheses were *plausible*, subjects at all levels tended to set an experimental goal of demonstrating key features of a given hypothesis, rather than conducting experiments that could discriminate between rival hypotheses. However, adults' response to *implausibility* was to propose a counter-hypotheses and then to conduct experiments that could discriminate between the two. In contrast, the third graders' general response to implausible hypotheses was to simply ignore them while attempting to demonstrate the correctness of a more plausible one of their own creation. By sixth grade, subjects appeared to understand how to generate informative experiments.

(b) Focus on only a few features of hypotheses. Experiments and hypotheses, are both complex entities having many aspects on which one could focus. Adults, but not children, were very conservative in the way they generated different experiments: they tended to design sequences of experiments that differed on only a single feature, whereas children tended to make multiple changes from one experiment to the next.

(c) Pragmatics. All but the youngest children (third graders) tended to create experiments that would not overwhelm their ability to observe and encode outcomes. The youngest children generated experiments with outcomes that, in principle, made clear distinctions between competing hypotheses, but that tended to be very hard to completely observe and/or recall, so that they were not effective. Thus, it seems that the youngest children had not yet developed sufficient metacognitive capacity to generate outcomes that were within their own perceptual and memory constraints (Brown, Bransford, Ferrara, & Campione, 1983).

These studies of children's problem-solving abilities involve problem solving in a "knowledge free" context. That is, while they reveal children's abstract reasoning abilities, they do not address questions about children's knowledge of the world. However, there is a rich literature on the development of children's concepts, and in the next section, we summarize studies that focus on specific concepts, and how they undergo change and development, rather than on problem-solving skills.

Conceptual Change in Children's Scientific Thought

One way in which children acquire new information is through conceptual change. Conceptual change refers to the process of reassigning a concept from one ontological category to another (Vosniadou, Vamvakoussi, & Skopeliti, 2008), such as when a child incorporates "plants" into his/her category of living things rather than inanimate objects. Conceptual change can also refer to the differentiation or the merging of concepts (Carey, 1991). Because conceptual change typically involves an ontological shift resembling the process of theory change, it can be distinguished from more incremental, additive, learning processes, in which gaps in students' knowledge are filled in or "enriched" by the addition of new information (Chi, 2008).

The extent to which children's concepts are organized is a highly contentious issue in conceptual change research. There is currently an active debate concerning whether children's conceptions are organized into coherent knowledge structures that have the consistency and predictive power, similar in many respects to scientific theories (Keil, 2011; Vosniadou & Brewer, 1992, 1994), or whether children represent knowledge in more context-dependent and fragmented ways (DiSessa, 2008; Smith, DiSessa, & Roschelle, 1994). Regardless of the nature of children's conceptual organization, it is clear that school-age children bring with them conceptions that differ from canonical scientific knowledge and that these preconceptions influence learning in a variety of scientific domains including physics (Clement, 1982), thermodynamics (Lewis & Linn, 1994), astronomy (Vosniadou & Brewer, 1994), biology (Inagaki & Hatano, 2008; Opfer & Seigler, 2004), geoscience (Gobert & Clement, 1999), and chemistry (Wiser & Smith, 2008). Moreover, conceptual change can occur for domain-general science concepts, such as learning the principles of experimental design (Siler, Klahr, & Matlen, in press) or understanding the purpose of scientific models (Grosslight, Unger, & Jay, 1991).

Preconceptions that are deeply rooted in children's everyday experiences are particularly resistant to instruction, and several studies have documented the continued existence of students' preconceptions even after semester-long courses in scientific domains (Clement, 1982; Lewis & Linn, 1994; Wiser & Smith, 2008). The underlying processes supporting conceptual change have been difficult to determine, although there have been a number of studies that have attempted to characterize the changes in knowledge representation that occur when switching from one way of representing scientific understanding to another (Carey, 1985; Chi, 1992; Chi & Roscoe, 2002; Clement, 1982; Thagard, 1992). One well-documented finding is that children construct new understanding on the basis of their prior knowledge, often by integrating teacher-provided information within the framework of their original skeletal beliefs (Vosniadou & Brewer, 1992, 1994). This process can lead to the adoption of "synthetic" understandings (Vosniadou & Brewer, 1994), characterized by a merging of information from instructional and noninstructional contexts. For instance, many early elementary-school children believe that the Earth is flat and that a person would eventually fall off the Earth if he or she were to walk straight for a long time. However, after being told that the Earth is in fact round, children can change their conception of the Earth to a round, disc-like object to account for what they are told (i.e., that the Earth is round) and what they observe (i.e., that the Earth is flat). Vosniadou and Brewer (1992) were able to identify a number of such synthetic understandings, including children's adoption of a dual earth model—where children believe there are two Earths: one in the sky, and another that comprises the flat ground where people live—or a hollow sphere model—where children believe that the Earth is a hollow sphere with a flat bottom on which we live. Facilitating conceptual change is thus a complex process that requires a detailed understanding of both the preconceptions children have and how those preconceptions are likely to change in the face of new information.

The idea that children undergo radical conceptual change in which old "theories" need to be overthrown or restructured has been a central topic of research on children's scientific thinking. Recent evidence suggests that rather than being replaced, preconceptions may continue to exist—and possibly compete with—scientifically accurate conceptions (Inagaki & Hatano, 2008). For example, adults are slower to categorize plants as living things than animals, even though they understand perfectly well that both are alive (Goldberg & Thompson-Schill, 2009), and under speeded conditions, adults sometimes will endorse teleological explanations in ways similar to children even though they reject such explanations under normal conditions (Kelemen & Rosset, 2009). These findings suggest that conceptual change may not be a process of "replacing" intuitive theories, but rather, that intuitive theories continue to exist alongside scientifically accurate ones (Schtulman & Valcarcel, 2011).

One strategy for inducing conceptual change is to introduce cognitive conflict—that is, to present children with information that conflicts with their existing conceptions. An example of a highly effective use of cognitive conflict comes from the domain of physics, where many students hold many misconceptions about forces. For instance, while a physicist understands that an object resting on a table has both downward (gravity) and upward (the table) forces acting upon it, many students believe that gravity alone is the only force acting upon the object. In a clever manipulation aimed at confronting students' misconceptions, Minstrell (1992) prompted his students to hold a book up with their hands and then asked them what forces were acting upon the object. When the students replied that gravity was the only force acting upon the object, Minstrell added an increasing number of books

to the stack until students realized that their hand was exerting an upward force to counteract the gravitational force. Once students had revised their conceptual model of compensating forces, they were able to generalize this new knowledge to explain the forces acting on the object resting on a table (Minstrell, 1992). Posner, Strike, Hewson, and Gertzog (1982) note that inducing cognitive conflict is a particularly effective instructional method when (a) students have a dissatisfaction with their preconceptions, (b) the instructor introduces a novel, alternative conception that is intelligible to the student, (c) the novel conception is initially plausible, and (d) the novel conception can be generalized to explain other, related phenomena. Because children revise their knowledge by constructing new knowledge that is initially intelligible, analogies are useful tools for producing conceptual change (discussed in the following section).

The Role of Analogy in Scientific Thinking

Analogy is one of the most widely mentioned reasoning processes used in science. Analogical reasoning is the process of aligning two or more representations on the basis of their common relational structure (Gentner, 1983, 2010). When one of the representations is better understood than the other, information from the familiar case (i.e., by convention, termed the "base") can be used to inform the scientist's understanding of the unfamiliar case (i.e., by convention, termed the "target"). Another form of analogical reasoning is when learning proceeds by drawing comparisons between two partially understood cases. Many scientists have claimed that the making of certain analogies was instrumental in their process of scientific discovery, and several theories of analogical reasoning suggest how analogy can play a role in scientific thinking (see Gentner, Holyoak, & Kokinov, 2001). Moreover, real-world studies of contemporary scientific laboratories (i.e., in vivo studies) have revealed that scientists commonly incorporate analogies to generate hypotheses, explain scientific phenomena, and interpret and construct scientific models (Dunbar, 1995, 1997, 2001; Nercessian, 2009).

Early developmental researchers believed that children were incapable of reasoning by analogy until they had reached a stage of formal operational reasoning (i.e., at around age 11, Piaget, Montangero, & Billeter, 1977; Sternberg & Nigro, 1980). However, there is now extensive evidence to indicate that children have at least rudimentary analogical ability at very young ages, and that this ability develops gradually with the increase of domain knowledge (Bulloch & Opfer, 2008; Goswami, 1991, 2001), executive function (Thibault, French, & Vezneva, 2010), and development of the prefrontal cortex (Wright, Matlen, Baym, Ferrer, & Bunge, 2008).

Although children's analogical reasoning is present at early ages, however, it is often distorted by an overreliance on superficial features at the expense of recognizing deeper, relational structure (Gentner, 1988; Richland, Morrison, & Holyoak, 2006). For example, third-grade children who learn the principles of experimental design readily apply the newly learned strategy to a different feature in the training set of materials (e.g., a ball and ramp apparatus). But they are much less likely to apply the same strategy when asked to design experiments with a novel set of materials that are superficially dissimilar from the trained set (e.g., springs and weights), even though the basic process for simple experimental design is the same in both cases (Chen & Klahr, 1999; Matlen & Klahr, 2010). Instructional strategies that attempt to promote analogical reasoning by focusing children's attention on abstract schemas, away from superficial appearances, have been shown to significantly increase the use of analogical reasoning (Goldstone & Son, 2005; Sloutsky, Kaminski, & Heckler, 2005).

One way for students to abstract knowledge is to engage in explicit comparison of analogous cases. This process appears to help students encode important analogical relationships (Gentner, 2010). For example, Kurtz, Miao, and Gentner (2001) had students compare two instances of heat transfer with familiar objects: students who jointly interpreted each scenario and listed similarities between the cases were more likely to refer to the causal schema of heat transfer than students who studied each case separately. Comparing analogous cases (e.g., by being provided with diagrams or probe questions that highlight the common structure) has been shown to be an effective scaffold for analogical reasoning in a wide array of scientific domains and even relatively mild manipulations—such as side-by-side presentation of examples—can be an effective way to foster children's analogical comparison (Christie & Gentner, 2010; Camtrambone & Holyoak, 1989; Gentner, Loewenstein, & Hung, 2007).

Another effective way to evoke comparison is to use analogies from familiar domains: For example, a teacher might relate the workings of a factory to the functioning of a cell (Glynn & Takahashi, 1998). Instructional analogies are particularly effective scaffolds for conceptual change because they (a) help to form a bridge between students' prior knowledge and novel, unfamiliar information, (b) they make it easier for students to notice important links between the base and target representations, and (c) they help in the process of visualizing complex or unobservable concepts (Dagher, 1995; Iding, 1997; Jee et al., 2010). Because instructional analogies derive their power in part from being familiar, teachers must ensure that the base analog is well understood by students. To these ends, students and teachers can explicitly map analogies together, making sure to point out relevant similarities as well as "where the analogy breaks down" to ameliorate the effects of negative transfer (Glynn, 1991). Because no analogy is perfect, multiple analogies that target specific relations can be an effective way of inducing scientific understanding (Chiu & Lin, 2005), and analogies can be sequenced such that they progressively bridge students' understanding of the similarity between the base and target concepts (Clement, 1993). More recent studies suggest that students learn best when analogy-enhanced text is accompanied by visuals (Matlen, Vosniadou, Jee, & Ptouchkina, 2011), and when teachers use spatial cues—such as gesturing between base and target concepts—to facilitate students' comparisons (Richland, Zur, & Holyoak, 2007).

Another core component of science is the ability to construct, interpret, and revise scientific models (Duit, 1991; Harrison & Treagust, 1998). Reasoning with a scientific model inevitably relies on the back and forth process of mapping relationships from the model (i.e., the base) and phenomenon the model is trying to explain (i.e., the target), therefore relying on

the process of inference projection and abstraction characteristic of analogical reasoning (Nersessian, 2002). While model-based reasoning is a relatively common practice in real-world science, it is rarely the focus of instruction in elementary education (Lehrer & Schauble, 2000). When a model's relational structure is supported by its superficial features, however, even young children can engage in relatively sophisticated reasoning with models. For example, Penner, Giles, Lehrer, & Schauble (1997) asked first-grade children to construct models of their elbow, and found that while children's models captured many superficial similarities (e.g., children insisted that their models include a hand with five fingers, represented by a foam ball and popsicle sticks), children were eventually able to construct models of their elbow that retained functional characteristics (e.g., incorporating the constraint that the elbow is unable to rotate 360°), and were also more likely than a nonmodeling peer group to ignore superficial distractors when identifying functional models. With sustained practice and scaffolding, children can overcome the tendency to attend to superficial similarities and can begin to reason with more abstract models that retain mostly relational structure, such as a graphing the relationship between plant growth and time (Lehrer & Schauble, 2004), or using a coin flip to model random variability in nature (Lehrer & Schauble, 2000). Often, superficial features can provide children the hook between perceiving relations between the model and the world, and as children gain experience and practice with modeling, superficial features can be progressively weaned away in favor of more abstract models.

The Role of Curiosity in Scientific Thinking

> *It is hard to satisfy the curiosity of a child, and even harder to satisfy the curiosity of a scientist.* (Bates, 1950)

Curiosity's role in scientific thinking is clear and unquestionably important. Curiosity involves recognizing when some information is missing or unknown. It motivates children to ask questions, make observations, and draw conclusions. Nevertheless, curiosity's role in these processes remains elusive, because there is no universally accepted definition of what it is (Jirout & Klahr, 2012). Defined in many different ways in the literature, operationalizations of curiosity can be categorized by level of specificity into three broad categories: curiosity as spontaneous exploration, curiosity as exploratory preference, and curiosity as preference for unknown and uncertainty.

When defining curiosity as exploratory behavior, researchers typically use observational measures of children playing, either with toys in a laboratory setting or in a highly stimulating environment, such as a museum. Any and all exploratory behaviors are considered to be curiosity, without consideration of children's differing levels of familiarity with the environment and materials, or the characteristics of the materials themselves. This method of studying curiosity has been used for studying children's maladaptive behavior (McReynolds, Acker, & Pietila, 1961), emotional and cognitive growth (Minuchin, 1971), and maternal behaviors (Endsley, Hutcherson, Garner, & Martin, 1979; Saxe & Stollak, 1971). Although the measure of curiosity as any exploratory behavior seems intuitively valid, the crucial element of stimuli characteristic is ignored. Additional factors are important to consider when using manipulations a child makes on an object as a measure of curiosity, such as the total opportunities or possibilities for manipulation on objects or the familiarity or novelty of an object. The use of inconsistent stimuli and a lack of consideration of both object familiarity and stimuli characteristics make it difficult to generalize any results beyond the limited scope of each study.

A more informative approach to studying curiosity—measuring children's exploratory preferences—involves determining specific factors that influence children's curiosity. In this approach, the total amount of exploratory behavior is not as important as the specific characteristics of objects or situations in which children choose to explore. Smock and Holt (1962) use preference for specific stimuli characteristics as a measure of curiosity. When given the opportunity to explore visual stimuli, preschool children were more likely to choose images higher in complexity, conflict, and incongruence, although there were wide individual differences in these choices. In addition, children preferred to play with an unknown toy to a known toy. Smock and Holt interpreted the characteristics of the preferred stimuli to be more general than complexity or incongruence, suggesting that the preferences were primarily driven by novelty, because children may have less experience with the type of complex, incongruent, and conflicting stimuli used in their study, and they suggest that this novelty is a more likely motivator of curiosity. A related approach to defining curiosity addresses the issue of children's curiosity as a novelty preference. The measurement of curiosity as a function of stimulus novelty assumes that more curious children prefer more novelty (Cantor & Cantor, 1964; Greene, 1964). There is empirical support for children's preference to explore novelty over familiarity, similar to the myriad studies on children's novelty preference unrelated to curiosity (Mendel, 1965). However, this work does not explain instances in which children prefer exploring familiar objects over novel ones, for example, children prefer exploring a known toy in which there is inconsistency, surprise, or ambiguity of its causal functions over a completely novel, unknown toy (Charlesworth, 1964; Schulz & Bonawitz, 2007). These examples are explained by the final approach to defining curiosity: curiosity as preference for the unknown, uncertainty, and ambiguity.

Instead of focusing on *stimuli* characteristics—that is, familiarity/novelty, complexity, and so on—this approach considers the relationship between the stimulus and the subject's knowledge, experience with, and understanding of the stimulus. These studies suggest that curiosity is a result of cognitive conflict or a gap in knowledge that is elicited by the stimuli or situation. For example, children are most curious when they see an outcome of an event that is inconsistent with their expectations (Charlesworth, 1964), when they don't understand how something works (Schulz & Bonawitz, 2007), and when they are aware of possible outcomes but aren't sure which will occur (Jirout & Klahr, 2009). With regard to the methods for measuring curiosity described above, measures of curiosity using uncertainty and ambiguity are the most specific and subsume the other methods used within their framework. Novelty, complexity, and the unknown can be interpreted as varying values on a continuum of uncertainty or ambiguity. The poles of this continuum—familiarity versus novelty, or known versus unknown—correspond to certain or unambiguous knowledge at one end of the spectrum, and total uncertainty and ambiguity at the other. After reviewing several theoretical perspectives on curiosity, Loewenstein (1994) arrived at the same conclusion and developed his Information-Gap Theory of curiosity, and Litman and Jimmerson (2004) developed their similar theory of curiosity as a feeling of deprivation. Both theories essentially defined curiosity in the same way, as the uncertainty/ambiguity measures discussed above, though Litman and Jimmerson also include a second type of curiosity similar to general interest.

Without a consistent operationalization of curiosity, it is difficult to discuss the role of curiosity in scientific thinking. Jirout and Klahr (2012) used the Information-Gap Theory to operationalize curiosity as the level of desired uncertainty in the environment most likely to lead to exploratory behavior. Studies of young children's curiosity, as defined here, suggest that curiosity is in fact related to children's ability to ask questions (Jirout & Klahr, 2011; Jirout, 2011). Children who are more curious—that is, those who prefer exploring greater uncertainty over less uncertainty—are also better at evaluating the effectiveness of questions and information in solving a mystery, and generate more questions overall (Jirout, 2011). When environments are experimentally manipulated to create varying amounts of uncertainty, both exploratory behavior (Litman, Hutchins, & Russon, 2005; Jirout & Klahr, 2009) and problem-solving accuracy (Mittman & Terrell, 1964) can be increased by creating an "optimal" level of uncertainty.

The curiosity literature supports the role of curiosity in scientific thinking as both a motivator of science and a crucial element of scientific reasoning, and the perceived importance of curiosity in science learning is evident by the inclusion of curiosity in all levels of science standards and goals (AAAS, 1993, 2008; Brenneman, Stevenson-Boyd, & Frede, 2009; Conezio & French, 2002; Kagan, Moore, & Bredekamp, 1995; National Education Goals Panel, 1995; NRC, 2000). Unfortunately, the body of knowledge about curiosity is limited. Although some will claim that "Real science begins with childhood curiosity..." (Conezio & French, 2002), further research is needed to better understand the role of curiosity in science learning.

SCIENTIFIC THINKING AND SCIENCE EDUCATION

Accounts of the nature of science and research on scientific thinking have had profound effects on science education at many levels, particularly in recent years. Up until the late 1970s, science education was primarily concerned with teaching students both the content of science (such as Newton's laws of motion), and the methods that scientists need to use in their research (such as using experimental and control groups). Beginning in the 1980s, a number of reports (e.g., AAAS, 1993; National Commission on Excellence in Education, 1983; Rutherford & Ahlgren, 1991) stressed the need for teaching children scientific thinking skills in addition to scientific procedures and content knowledge. This addition of scientific thinking skills to the science curriculum—from kindergarten through post-secondary levels—was a major shift in focus. Many of the particular scientific thinking skills that have been emphasized in this augmentation of the classical curriculum have been described in this chapter, such as teaching deductive and inductive thinking strategies. However, rather than focusing on any one specific skill, such as induction, researchers in science education have focused on ways to integrate the various components of scientific thinking, as well has how to better understand, and improve, collaborative scientific thinking.

What is the best way to teach and learn science? A clear, empirically supported, answer to this question has proven surprisingly elusive. For example, toward the end of the last century, influenced by several thinkers who advocated a constructivist approach to learning, ranging from Piaget (Beilin, 1994) to Papert (1978), many schools answered this question by adopting a philosophy dubbed "discovery learning." Although a clear operational definition of this approach has yet to be articulated, the general idea is that children are expected to learn science by reconstructing the processes of scientific discovery—in a range of areas from computer programming to chemistry to mathematics. The premise is that letting students discover principles on their own, set their own goals, and collaboratively explore the natural world, produces deeper knowledge that transfers widely. This approach sees learning as an active rather than a passive process, and suggests that students learn through constructing their scientific knowledge. We will first describe a few examples of the constructivist approach to science education. Following that, we will address several lines of work that challenge some of the assumptions of the constructivist approach to science education.

Often the goal of constructivist science education is to produce conceptual change through guided instruction where the teacher or professor acts as a guide to discovery, rather than the keeper of all the facts. One recent and influential approach to science education is the inquiry-based learning approach. Inquiry-based learning focuses on posing a problem or a puzzling event to students, and asking them to propose a hypothesis that could explain the event. Next, the student is asked to collect data that tests the hypothesis, make conclusions, and then reflect upon both the original problem and the thought processes that they used to solve the problem. Often students use computers that aid in their construction of new knowledge. The computers allow students to learn many of the different components of scientific thinking. For example, Reiser and his colleagues have developed a learning environment for biology, where students are encouraged to develop hypotheses in groups, codify the hypotheses, and search databases to test these hypotheses (Reiser, et al., 2001).

The research literature on science education is far from consistent in its use of terminology. However, our reading suggests that "Discovery learning" differs from "inquiry-based learning" in that few, if any, guidelines are given to students in discovery learning contexts, whereas in inquiry learning, students are given hypotheses, and specific goals to achieve. Although thousands of schools have adopted discovery learning as an alternative to more didactic approaches to teaching and learning, the evidence showing that it is more effective than traditional, direct, teacher-controlled instructional approaches is mixed, at best (Lorch et al., 2010; Minner, Levy, & Century, 2010). In several cases where the distinctions between direct instruction and more open-ended constructivist instruction have been clearly articulated, implemented, and assessed, direct instruction has proven to be superior to the alternatives (Chen & Klahr, 1999; Toth, Klahr, & Chen, 2000). For example, in a study of third- and fourth-grade children learning about experimental design, Klahr and Nigam (2004) found that many more children learned from direct instruction than from discovery learning. Furthermore, they found that among the few children who did manage to learn from a discovery method, there was no better performance on a far transfer test of scientific reasoning than that observed for the many children who learned from direct instruction.

The idea of children learning most of their science through a process of self-directed discovery has some romantic appeal, and it may accurately describe the personal experience of a handful of world-class scientists. However, the claim has generated some contentious disagreements (Kirschner, Sweller, & Clark, 2006; Klahr, 2009, 2010; Taber, 2010; Tobias & Duffy, 2009), and the jury remains out on the extent to which most children can learn science that way.

As noted above, scientific thinking involves thinking about both the *content* of science and the process of *"doing"* science. A recent NRC report describes a similar framework for science education (NRC, 2011). The overall framework of the report (see Table 9.1) includes three dimensions of science education: (a) scientific practices, which are general processes of science such as question asking, using models, and communicating information, (b) core ideas, including domain-specific topics like energy and evolution, and (c) cross-cutting concepts such as recognizing patterns.

On the basis of the assumption that understanding develops over time, the report emphasizes the importance of creating a framework with which to build on throughout K-12 science education, giving specific examples of learning progressions for different topics and concepts, and how to recognize understanding of the content taught at different grade levels. For example, in the domain "Organization for Matter and Energy Flow in Organisms," one set of goals, by grade, for students' scientific practices are: second grade students should be able to present information about why animals can be classified into simple groups, fifth grade students should be able to support claims using evidence, eighth grade students should be able to elaborate on arguments using explanations, and twelfth grade students should be able to present these arguments and explanations using sophisticated methods such as diagrams and models. The report also gives explicit suggestions on the depth of the standards that should be included in the more concrete, domain-specific content taught. To address the "mile wide and inch deep" issue, the report focuses on four main content areas to be covered: physical science, life science, Earth and space science, and engineering, technology, and the applications of science. The authors caution against including too many standards, and even suggest including what should *not* be taught as a way of keeping the standards manageable. The final dimension of science education addressed in the report is "cross-cutting concepts," another set

Table 9.1 *Framework for K-12 Science Education*

1. Scientific and Engineering Practices	
1. Asking questions (for science) and defining problems (for engineering)	
2. Developing and using models	
3. Planning and carrying out investigations	
4. Analyzing and interpreting data	
5. Using mathematics and computational thinking	
6. Constructing explanations (for science) and designing solutions (for engineering)	
7. Engaging in argument from evidence	
8. Obtaining, evaluating, and communicating information	
2. Cross-Cutting Concepts	
1. Patterns	
2. Cause and effect: Mechanism and explanation	
3. Scale, proportion, and quantity	
4. Systems and systems models	
5. Energy and matter: Flows, cycles, and conservation	
6. Structure and function	
7. Stability and change	
3. Disciplinary Core Ideas	
Physical Sciences	
PS 1: Matter and its interactions	
PS 2: Motion and stability: Forces and interactions	
PS 3: Energy	
PS 4: Waves and their applications in technologies for information transfer	
Life Sciences	
LS 1: From molecules to organisms: Structures and processes	
LS 2: Ecosystems: Interactions, energy, and dynamics	
LS 3: Heredity: Inheritance and variation of traits	
LS 4: Biological evolution: Unity and diversity	
Earth and Space Sciences	
ESS 1: Earth's place in the universe	
ESS 2: Earth's systems	
ESS 3: Earth and human activity	
Engineering, Technology, and the Applications of Science	
ETS 1: Engineering design	
ETS 2: Links among engineering, technology, science, and society	

Source: Adapted from NRC, 2011.

of domain-general skills that are considered to be different from the scientific practices. These include patterns; cause and effect; scale, proportion, and quantity; systems and system models; energy and matter; flows, cycles, and conservation; structure and function; and stability and change. These concepts "provide students with an organizational framework for connecting

knowledge from the various disciplines into a coherent and scientifically based view of the world." Although the report concedes that research on teaching these concepts is limited, it emphasizes the importance of developing these concepts as a way of instilling a common vocabulary and framework for learning across the core science domains. The report emphasizes the importance of integrating the three dimensions of science education, and provides examples of how this can be accomplished.

The authors of this framework acknowledge that it is only the beginning of a challenging process of improving science education, and they discusses issues of curriculum and instruction, teacher development, and assessments. An entire chapter is devoted to diversity and equity, and the importance of providing children a fair opportunity to learn. Recommendations for creating science standards are provided, and suggestions are made for research that is needed to effectively implement the provided framework and inform future revisions.

CONCLUSIONS AND FUTURE DIRECTIONS

In this chapter, we have argued that the basic cognitive processes used in everyday reasoning are the same processes used to make scientific discoveries. That is, the type of thinking that is deemed "scientific" and other traditional forms of thinking have more similarities than differences. Furthermore, we suggest that children are capable of such scientific thinking and that they employ it when learning scientific content, albeit at levels appropriate to their development. We have also offered suggestions for fostering scientific thinking in science education, including scaffolding children's scientific thinking through the use of explicit and guided-inquiry instruction.

At a course grain, the arguments we present in this chapter may seem somewhat paradoxical. On the one hand, we have suggested that children have many of the same basic reasoning abilities as scientists. This argument seems consistent with the constructivist notion that an optimal way to proceed with science education is to let children discover, on their own, scientific phenomena in much the same way that real-world scientists have throughout the course of history. On the other hand, we have suggested that an effective way to teach science—at least to domain novices—is to provide more directed guidance when a child engages in inquiry processes. Are these arguments necessarily inconsistent? We think not, for several reasons. First, while young children are indeed capable of employing many reasoning processes integral to scientific discovery, the developmental course of such reasoning processes is protracted, and extends even into adult education. Thus, children would likely benefit from some degree of scaffolding to avoid practicing incorrect strategies and more efficiently learn correct strategies. Second, guided and explicit instruction can be designed so as to use children's (often erroneous) preconceptions as starting points, an approach that is consistent with constructivism. Finally, the discoveries made by real-world scientists have sometimes taken centuries to achieve, and expecting young children to spontaneously recreate such discoveries is unrealistic. Withholding explicit guidance may indeed be beneficial for children once they have gained some expertise in science concepts (Kalyuga, 2007), however, expecting children to succeed in minimally guided settings is likely to lead to frustration and floundering (Koedinger & Aleven, 2007). Instead, we suggest that children should engage in sustained practice in scientific reasoning throughout their science careers and that providing guidance and feedback throughout this process can lead to optimal science learning outcomes.

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