Goals for Science Education

Science is built up of facts as a house is of stones, but a collection of facts is no more a science than a pile of stones is a house.

Henri Poincare, *La Science et l’Hypothèse* (1908)

Before one can discuss the teaching and learning of science, consensus is needed about what science is and why it should occupy a place in the K-8 curriculum. One must ask: "What is science?" and "Why teach it"? A consensus answer to these fundamental questions is not easily attained, because science is characterized in different ways not only by different categories of people interested in it—practitioners, philosophers, historians, educators—but also by people within each of these broad categories. In this chapter, we describe some different characterizations of science and consider implications for what is taught in science classrooms. Although the characterizations share many common features, they vary in the emphasis and priority they place on different aspects of scientific activity, with potential consequences for what is emphasized in science classrooms. We then describe the goals of science education associated with each perspective.

WHAT IS SCIENCE?

Science is both a body of knowledge that represents current understanding of natural systems and the process whereby that body of knowledge has been established and is being continually extended, refined, and revised. Both elements are essential: one cannot make progress in science without an understanding of both. Likewise, in learning science one must come to understand both the body of knowledge and the process by which this knowledge is established, extended, refined, and revised. The various perspectives on science—alluded to above and described below—differ mainly with respect to the process of science, rather than its product. The body of knowledge includes specific facts integrated and articulated into highly developed and well-tested theories. These theories, in turn, can explain bodies of data and predict outcomes of experiments. They are also tools for further development of the subject. An important component of science is the knowledge of the limitations of current theories, that is, an understanding of those aspects of a theory that are well tested and hence are well established, and of those aspects that are not well tested and hence are provisional and likely to be modified as new empirical evidence is acquired.

The process by which scientific theories are developed and the form that those theories take differ from one domain of science to another, but all sciences share certain common features...
at the core of their problem-solving and inquiry approaches. Chief among these is the attitude that data and evidence hold a primary position in deciding any issue. Thus, when well-established data, from experiment or observation, conflict with a theory or hypothesis, then that idea must be modified or abandoned and other explanations must be sought that can incorporate or take account of the new evidence. This also means that models, theories, and hypotheses are valued to the extent that they make testable (or in principle testable) precise predictions for as yet unmeasured or unobserved effects; provide a coherent conceptual framework that is consistent with a body of facts that are currently known; and offer suggestions of new paths for further study.

A process of argumentation and analysis that relates data and theory is another essential feature of science. This includes evaluation of data quality, modeling, and development of new testable questions from the theory, as well as modifying theories as data dictates the need. Finally, scientists need to be able to examine, review, and evaluate their own knowledge. Holding some parts of a conceptual framework as more or less established and being aware of the ways in which that knowledge may be incomplete are critical scientific practices.

The classic scientific method as taught for many years provides only a very general approximation of the actual working of scientists. The process of theory development and testing is iterative, uses both deductive and inductive logic, and incorporates many tools besides direct experiment. Modeling (both mechanical models and computer simulations) and scenario building (including thought experiments) play an important role in the development of scientific knowledge. The ability to examine one’s own knowledge and conceptual frameworks, to evaluate them in relation to new information or competing alternative frameworks, and to alter them by a deliberate and conscious effort are key scientific practices.

**Different Perspectives on the Process of Science**

Those who study the nature of science and the learning of science have a variety of perspectives not only on key elements of scientific practice and skills (Stanovich, 2003; Grandy and Duschl, 2005), but also on different ways to study the nature of science (see Klahr and Simon, 1999; Proctor and Capaldi, 2005; Giere, 1999). The committee recognizes that these different perspectives are not mutually exclusive and that, in considering how best to teach science, each can identify certain elements that need to be given their due attention. We summarize the key elements of a number of these viewpoints.¹

**Science as a Process of Logical Reasoning About Evidence**

One view of science, favored by many psychologists who study scientific reasoning, emphasizes the role of domain-general forms of scientific reasoning about evidence, including formal logic, heuristics, and problem-solving strategies. Among psychologists, this view was pioneered by the work of Inhelder and Piaget (1958) on formal operations, by the studies of Bruner, Goodnow, and Austin (1956) on concept development, and by investigations by Wason (1960, 1968) of the type of evidence that people seek when testing their hypotheses. The image of scientist-as-reasoner continues to be influential in contemporary research (Case and Griffin, 1990). In this view, learning to think scientifically is a matter of acquiring problem-solving

¹ This discussion of the different views of science is based on Lehrer and Schauble (2006). Scientific thinking and science literacy.
strategies for coordinating theory and evidence (Klahr, 2000; Kuhn, 1989), mastering counterfactual reasoning (Leslie, 1987), distinguishing patterns of evidence that do and do not support a definitive conclusion (Amsel and Brock, 1996; Beck and Robinson, 2001; Fay and Klahr, 1996; Vellom and Anderson, 1999), and understanding the logic of experimental design (Tschirgi, 1980; Chen and Klahr, 1999). These heuristics and skills are considered important targets for research and for education because they are assumed to be widely applicable and to reflect at least some degree of domain generality and transferability (Kuhn, et al., 1995; Ruffman, et al., 1993).

Science as a Process of Theory Change

This view places emphasis on the parallel between historical and philosophical aspects of science (Kuhn, 1962) and the domains of cognitive development (Carey, 1985; Koslowski, 1996) in which domain-specific knowledge evolves via the gradual elaboration of existing theories through the accretion of new facts and knowledge (normal science, according to Kuhn), punctuated, occasionally, by the replacement of one theoretical framework by another. The science-as-theory perspective places its emphasis less on the mastery of domain-general logic, heuristics, or strategies and more on processes of conceptual or theory change. In this view, at critical junctures, as evidence anomalies build up against the established theory, there can occur wholesale restructurings of the theoretical landscape—a paradigm shift, according to Kuhn (1962). For example, in both Kuhn's account of scientific revolutions and Chi's (1992) and Carey's (1988, 1991) accounts of critical points of conceptual restructuring in cognitive development, not only do new concepts enter a domain, but also existing concepts change their meaning in fundamental ways because the theoretical structure within which they are situated radically changes (e.g., changes in concepts like force, weight, matter, combustion, heat or life). Nersessian (1989) provides a good example of the semantic changes that occur when motion and force are examined across Aristotelian, Galilean, and Newtonian frameworks.

Science as a Process of Participation in the Culture of Scientific Practices

The view of science as practice is emphasized by anthropologists, ethnographers, social psychologists, and the cognitive and developmental psychologists who study “situated cognition” (Brown, Collins, and Duguid, 1989; Lave and Wenger, 1991; Latour, 1990, 1999; Rogoff and Lave, 1984). This view focuses on the nature of scientific activity, both in the short term (e.g., studies of activity in a particular laboratory or a program of study) and historically (e.g., studies of laboratory notebooks, published texts, eyewitness accounts). Science as practice suggests that theory development and reasoning are components of a larger ensemble of activity that includes networks of participants and institutions (Latour, 1999; Longino, 2002); specialized ways of talking and writing (Bazerman, 1988); modeling, using either mechanical and mathematical models or computer-based simulations (Nersessian, 2005); and development of representations that render phenomena accessible, visualizable, and transportable (Gooding, 1989; Latour, 1990; Lehrer and Schauble, 2006).

This perspective serves as a useful foil to the tendency of “pure” cognitive approaches to science to minimize the fact that individual scientists or groups of scientists are always part of a wider social environment, inside and outside science, with which they are in constant communication and which has strongly shaped their knowledge, skills, resources, motives, and
attitudes. This interaction between social and cognitive factors is well illustrated in Thagard’s (1999a, 1999b) account of the pioneering research by Barry Marshall and Robin Warren. They received the Nobel prize in medicine in 2005 for their discovery of the bacterial origins of stomach ulcers. Until 1983, the prevailing view was that gastric ulcers were caused by lifestyle and stress. When Marshall and Warren suggested that ulcers were caused by the bacterium *Helicobacter pylori*, their claim was viewed as preposterous by the medical research establishment, but the weight of empirical evidence soon overwhelmed deeply entrenched and widely accepted scientific beliefs. The reasons for both the initial and final positions in the field clearly involve important social mechanisms that go beyond simple evidence-based reasoning processes. However, to acknowledge the influence of situated, social, and noncognitive factors in the process of scientific discovery is not to deny the existence of an external physical reality that science attempts to discover and explain (see for example Pickering, 1995).

**Language of Science**

In science, words often are given very specific meanings that are different from and often more restrictive than their everyday usage. A few such cases are important to discuss before we proceed further in this report. It is also important for teachers to be aware of the confusion that can arise from these multiple usages of familiar words, clarifying the specific scientific usage when needed.

**Theory and Hypothesis**

A scientific theory (particularly one that is referred to as “the theory of ___,” as in the theory of electromagnetism or the theory of thermodynamics or the theory of Newtonian mechanics) is an explanation that has undergone significant testing. Through those tests and the resulting refinement, it takes a form that is a well-established description of, and predictor for, phenomena in a particular domain. A theory is so well established that it is unlikely that new data within that domain will totally discredit it; instead, the theory may be modified and revised to take into account new evidence. There may be domains in which the theory can be applied but has yet to be tested; in those domains the theory is called a working hypothesis. Indeed the term "hypothesis" is used by scientists for an idea that may contribute important explanations to the development of a scientific theory. Scientists use and test hypotheses in the development and refinement of models and scenarios that collectively serve as tools in the development of a theory.

"Theory" has at least two other meanings, and these other meanings differ in important ways from the above use of the term. One alternative use of the term comes from psychological research. Researchers in cognitive development have investigated the way in which children come to understand the world around them and have attributed to them a wide variety of immature and inadequate—albeit pervasive—"theories" about the world. Psychologists use the term "theory" here as a shorthand for the set of ideas and beliefs that forms the child's conceptual framework for explaining phenomena and mechanisms. This usage is closer to the everyday usage of the word "theory" as an idea or conjecture rather than as a complex explanation supported by evidence. It does not imply that a child’s theory is a scientific theory in the sense defined above. However, a conceptual framework takes the place of a scientific theory in the way that the child uses it to process information and to view and interact with external events; hence the interplay between instruction and a child's conception of the world is an important issue for the teaching of science.
The second alternative meaning comes from everyday language, in which "theory" is often indistinguishable in its use from "guess," "conjecture," "speculation," "prediction," or even "belief" (e.g., "My theory is that indoor polo will become very popular" or “My theory is that it will rain tomorrow”). Such “theories” are typically very particular and have no broader conceptual scope. Popular usage also confuses the ideas of scientific fact and a scientific theory, which we distinguish by example in the discussion below.

Data and Evidence

A datum is an observation or measurement recorded for subsequent analysis. The observation or measurement may be of a natural system or of a designed and constructed experimental situation. Observation here includes indirect observation, which uses inference from well-understood science, as well as direct sensory observations. Thus the assertion that a particular skeleton comes from an animal that lived during a particular geological period is based on acceptance of the body of knowledge that led to the widely accepted techniques used to date the bones, techniques that are themselves the products of prior scientific study. “Observations” in the research laboratory, particularly observations of events and phenomena whose duration or size is inaccessible to the unaided human perceptual system, often include a substantial chain of such inferences. In the elementary and middle school classroom, observation usually involves fewer inferences. For example, students may begin by conducting unaided observations of natural phenomena and then progress to using simple measurement tools or instruments such as microscopes.

Some use the term “scientific claim” for a well-established property, correlation, or occurrence, directly based on well-validated observation or measurement. When a scientific claim is demonstrated to occur forever and always in any context, scientists will refer to the claim as a fact (e.g., the sun rises in the east). Facts are best seen as evidence and claims of phenomena that come together to develop and refine or to challenge explanations. For example, the fact that earthquakes occur has been long known, but the explanation for the fact that earthquakes occur takes on a different meaning if one adopts plate tectonics as a theoretical framework. The fact that there are different types of earthquakes (shallow and deep focus) helps to deepen and expand the explanatory power of the theory of plate tectonics.

A century ago the atomic substructure of matter was a theory, which became better established as new evidence and inferences based on this evidence deepened the complexity and explanatory power of the theory. Today, atoms are an established component of matter due to the modern capability of imaging individual atoms in matter with such tools as scanning-tunneling microscopes. This kind of progression from theoretical construct to observed property leads to some confusion in the mind of many people about the nature of theory and the distinctions between theory, evidence, claims, and facts. The history of science further reveals that theories progress from hypotheses or tentative ideas to core explanations.

Thus, another source of confusion for the public understanding of science is the use of the term “theory” to represent promising ideas as well as core explanatory theories. Core explanatory theories are those that are firmly established through accumulation of a substantial body of supporting evidence and have no competitors; (e.g., cell theory, periodic law, theory of evolution, theory of plate tectonics). For much of science, theories are broad conceptual frameworks that can be invalidated by contradictions with data but can never be wholly validated.
To give a specific example: it is an observed property that things fall down when dropped near the surface of the earth. Repeated observations give the rate of acceleration in this event, both its global average and local variations from that average. Newton's law of universal gravitation and Einstein's general theory of relativity are two successive theories that incorporate this observation and give quantitative predictions for the size of the gravitational effects in any situation, not just on earth. These theories describe but do not actually explain gravitation in the conventional sense of that word; they invoke no underlying mechanism due to substructure and subsystems. The general theory of relativity includes Newton's law of gravitation as a special limited case (an approximation or idealization, valid to high accuracy under certain conditions), but it is a more general theory that makes predictions for cases not covered by Newton's law (e.g., the bending of light paths by the sun or other stars).

In this example, drawn from physics, the theories are expressed in mathematical form and their predictions are thus both precise and specific. They lend themselves readily to computer modeling and simulation. In other areas of science, theories can take more linguistic forms and involve other types of models. What is general is that scientific theories are valued when they (a) incorporate a significant body of evidence in a single conceptual framework and (b) offer predictive suggestions about future directions for study that are specific enough that one can test the theory’s validity and domain of applicability. A theory may or may not include a mechanism for the effects it describes and predicts.

Another important feature of the example is that it challenges a common perception of scientific revolutions. Einstein’s general theory of relativity was a true scientific revolution, in that it challenged and redefined conceptions of the nature of space and time. However, it did not invalidate all that had gone before; instead, it showed clearly both the limitations of the previous theory and the domain in which the previous theory is valid as an excellent (close) approximation, useful because it is much simpler (both conceptually and mathematically) than the full general theory of relativity.

This is a key understanding: science is subject to development and change, yet well-tested and established theories remain true in their tested domain even when dramatic new ideas or knowledge changes the way one views that domain. Such theories are tentative in domains in which they have not yet been tested, or in which only limited data are available, so that the tests are not yet conclusive but are far from tentative in the domains in which they have repeatedly been tested through their use in new scientific inquiries.

Argument

In everyday usage, an argument is an unpleasant situation in which two or more people have differing opinions and become heated in their discussion of this difference. A somewhat different view of the term “argument” comes from the tradition of formal debate, in which contestants are scored on arguments that favor a particular position or point of view or disfavor the opposing one. Argumentation in science has a different and less combative or competitive role than either of these forms (Kuhn, 1991). It is a mode of logical discourse whose goal is to tease out the relationship between ideas and the evidence—for example, to decide what a theory or hypothesis predicts for a given circumstance, or whether a proposed explanation is consistent or not with some new observation. The goal of those engaged in scientific argumentation is a common one: to tease out as much information and understanding from the situation under discussion as possible. Alternative points of view are valued as long as they contribute to this
process within the accepted norms of science and logic, but not when they offer alternatives that are viewed as outside those norms. Because the role, mode, and acceptance of argument, in its everyday sense, cultural variables, it is important to teach skills and acceptable modes of scientific argumentation, and for both teachers and students to learn by experience the difference between this form of discourse and their preconceived notions of what “wins” an argument.

**SCIENCE EDUCATION**

**Why Teach Science?**

In the modern world, some knowledge of science is essential for everyone. It is the opinion of this committee that science should be as nonnegotiable a part of basic education as are language arts and mathematics. It is important to teach science because:

1. Science is a significant part of human culture and represents one of the pinnacles of human thinking capacity.
2. It provides a laboratory of common experience for development of language, logic, and problem-solving skills in the classroom.
3. A democracy demands that its citizens make personal and community decisions about issues in which scientific information plays a fundamental role, and they hence need a knowledge of science as well as an understanding of scientific methodology.
4. For some students, it will become a lifelong vocation or avocation.
5. The nation is dependent on the technical and scientific abilities of its citizens for its economic competitiveness and national needs.

**What Should Be the Goals of Elementary and Middle School Science?**

To quote Albert Einstein, the goal of education is “to produce independently thinking and acting individuals.” The eventual goal of science education is to produce individuals capable of understanding and evaluating information that is, or purports to be, scientific in nature and of making decisions that incorporate that information appropriately, and, furthermore, to produce a sufficient number and diversity of skilled and motivated future scientists, engineers, and other science-based professionals.

The science curriculum in the elementary grades, like that for other subject areas, should be designed for all students to develop critical basic knowledge and basic skills, interests, and habits of mind that will lead to productive efforts to learn and understand the subject more deeply in later grades. If this is done well, then all five of the reasons to teach science will be well served. It is not necessary in these grades to distinguish between those who will eventually become scientists and those who will chiefly use their knowledge of science in making personal and societal choices. A good elementary science program will provide the basis for either path in later life.

The specific content of elementary school science has been outlined in multiple documents, including the *National Science Education Standards*, the *Benchmarks for Science Literacy*, and multiple state standards documents. Teachers are held accountable to particular state and local requirements. It is not the role of this report to specify a list of content to be taught. However, it is important to note that what this report says about science learning always
assumes that there is a strong basis of factual knowledge and conceptual development in the science curriculum, and that the goal of any methodology for teaching is to facilitate student learning and understanding of this content, as well as developing their skills in, and understanding of, the methods of scientific observation, experimentation, modeling, and analysis.

It is often said that children are natural scientists. Experts in child development have debated this issue, not on the basis of the basic facts of children's behavior, but rather on the relation between that behavior and the essential aspects of scientific thinking (Giere, 1996; Gopnik, 1996; Gopnik and Wellman, 1992; Harris, 1994; Kuhn, 1989; Metz, 1995, 1997; Vosniadou and Brewer, 1992, 1994). Rather than attempting to resolve this debate, we simply acknowledge the fact that children bring to science class a natural curiosity and a set of ideas and conceptual frameworks that incorporate their experiences of the natural world and other information that they have learned. Since these experiences vary, children at a given age have a wide range in their skills, knowledge, and conceptual development. A teacher therefore needs to be able to evaluate each child’s knowledge and conceptual and skill development, as well as the child’s level of meta-cognition about his or her own knowledge, skills, and concepts, in order to provide a learning environment that moves each child’s development in all these areas. A key question for instruction is thus how to adapt the instructional goals to the existing knowledge and skills of the learners, as well as how to choose instructional techniques that will be most effective.

Each of the views of science articulated above highlights particular modes of thought that are essential to that view. These views are not mutually exclusive descriptions of science, but rather each stresses particular aspects. Since students need to progress in all aspects, it is useful for teachers to have a clear understanding of each of these components of scientific development, just as they need a clear understanding of the subject matter, the specific science content, that they are teaching. It is also useful at times to focus instruction on development of specific skills, in balance with a focus on the learning of specific facts or the understanding of a particular conceptual framework.

Thus, if one looks from the perspective of science as a process of reasoning about evidence, one sees that logical argumentation and problem-solving skills are important. Certain aspects of meta-cognition are also highlighted, such as the ability to be aware when one’s previously held convictions are in conflict with an observation. If one looks at science as a process of theory change, one sees that teachers must recognize the role of students’ prior conceptions about a subject and facilitate the necessary processes of conceptual change and development. Finally, when one looks at science as a process of participation in the culture of scientific practice, attention is drawn to the ways in which children’s individual cultural and social backgrounds can, on one hand, create barriers to science participation and learning due to possible conflicts of cultural norms or practices with those of science, and, on the other hand, provide opportunities for contributions, particularly from students from nonmainstream cultures, that enrich the discourse in the science classroom. One also sees a range of practices, such as model building and data representation, that each in itself is a specific skill and thus needs to be incorporated and taught in science classrooms.

It is thus clear that multiple strategies are needed, some focused primarily on key skills or specific knowledge, others on particular conceptual understanding, and yet others on meta-cognition. The issues of what children bring to school and of how teaching can build on it to foster robust science learning with this rich multiplicity of aspects are the core topics of this report.
Strands of Scientific Proficiency

Understanding science is multifaceted. Research has often treated aspects of scientific proficiency as discrete. However, current research indicates that proficiency in one aspect of science is closely related to proficiency in others (e.g., analytic reasoning skills are greater when one is reasoning about familiar domains). Like strands of a rope, the strands of scientific proficiency are intertwined. However, for purposes of being clear about learning and learning outcomes, the committee discusses these four strands separately (see Box 2-1 for a summary).

The strands of scientific proficiency lay out broad learning goals for students. They address the knowledge and reasoning skills that students must eventually acquire to be considered fully proficient in science. They are also a means to that end: they are practices that students need to participate in and become fluent with in order to develop proficiency.

Students who understand science:
1. Know, use, and interpret scientific explanations of the natural world.
2. Generate and evaluate scientific evidence and explanations.
3. Understand the nature and development of scientific knowledge.
4. Participate productively in scientific practices and discourse.

The strands are not independent or separable in the practice of science, nor in the teaching and learning of science. Rather, the strands of scientific proficiency are interwoven and, taken together, are viewed as science as practice (see Lehrer and Schauble, 2006). The science-as-practice perspective invokes the notion that learning science involves learning a system of interconnected ways of thinking in a social context to accomplish the goal of working with and understanding scientific ideas. This perspective stresses how conceptual understanding of natural systems is linked to the ability to develop explanations of phenomena and to carry out empirical investigations in order to develop or evaluate knowledge claims.

The strands framework emerged through the committee’s syntheses of disparate research literatures on learning and teaching science, which define science outcomes differently and frequently do not inform one another. The framework offers a new perspective on what is learned when students learn science. First, the strands emphasize the idea of knowledge in use. That is, students’ knowledge is not static, and proficiency involves deploying knowledge and skills across all four strands in order to engage successfully in scientific practices. The content of each strand described below is drawn from research and differs from many typical presentations of goals for science learning. For example, we include an emphasis on theory building and modeling, which is often missing in existing standards and curricular frameworks. And, the fourth strand is often completely overlooked, but research indicates it is a critical component of science learning, particularly for students from populations that are typically underrepresented in science.

These strands illustrate the importance of moving beyond a simple dichotomy of instruction in terms of science as content or science as process. That is, teaching content alone is not likely to lead to proficiency in science, nor is engaging in inquiry experiences devoid of meaningful science content. Rather, students across grades K-8 are more likely to advance in their understanding of science when classrooms provide learning opportunities that attend to all four strands.
**Know, Use, and Interpret Scientific Explanations of the Natural World**

Knowing, using, and interpreting scientific explanations encompasses learning the facts, concepts, principles, laws, theories and models of science. As the *National Science Education Standards* state (National Research Council, 1996, p. 23):

Understanding science requires that an individual integrate a complex structure of many types of knowledge, including the ideas of science, relationships between ideas, reasons for these relationships, ways to use the ideas to explain and predict other natural phenomena, and ways to apply them to many events.

Understanding natural systems requires knowledge of conceptually central ideas and facts integrated in well-structured knowledge systems, that is, facts integrated and articulated into highly developed and well-established theories. In the science-as-practice framework, we emphasize that these theories or models—the “big ideas” or powerful explanatory models of science—are what enable learners to construct explanations about natural phenomena, including novel cases not exactly like those previously experienced. This strand stresses acquiring facts, building organized and meaningful conceptual structures that incorporate these facts, and employing these conceptual structures during the interpretation, construction, and refinement of explanations, arguments, or models.

**Generate and Evaluate Scientific Evidence and Explanations**

Generating and evaluating scientific evidence and explanations encompasses the knowledge and skills used for building and refining models and explanations (conceptual, computational, mechanistic), designing and analyzing empirical investigations and observations, and constructing and defending arguments with empirical evidence. This strand also incorporates the social practices (e.g., critiquing an argument) and tools (conceptual, mathematical, physical, and computational) fundamental to constructing and evaluating knowledge claims. Hence, it includes a wide range of practices involved in designing and carrying out a scientific investigation, including asking questions, deciding what to measure, developing measures, collecting data from the measures, structuring the data, interpreting and evaluating the data, and using the empirical results to develop and refine arguments, models, and theories.

**Understand the Nature and Development of Scientific Knowledge**

This strand focuses attention on students’ understanding of science as a way of knowing: the nature of scientific knowledge, the nature of theory and evidence in science, and the sources for, justification of, and certainty of scientific knowledge. It also includes students’ reflection on the status of their own knowledge.

This strand includes developing a conception of “doing science” that extends beyond experiment to include modeling, systematic observation, and historical reconstruction. It also includes an awareness that science entails the search for core explanatory constructs and connections between them. More specifically, students must recognize that there may be multiple interpretations of the same phenomena. They must understand that explanations are increasingly
valuable as they account for the available evidence more completely, and as they generate new, productive research questions. Students should be able to step back from evidence or an explanation and consider whether another interpretation of a particular finding is plausible with respect to existing scientific evidence and other knowledge that they hold with confidence. This entails embracing a point of view as possible and worthy of further investigation, but subject to careful scrutiny and consideration of alternative perspectives (which may be deemed more valuable in the end).

**Participate Productively in Scientific Practices and Discourse**

To understand science, one must use science and do so in a manner that reflects the values of scientific practice. Participation is premised on a view that science and scientific knowledge are valuable and interesting, seeing oneself as an effective learner and participant in science, and the belief that steady effort in understanding science pays off. These attitudes toward science and science learning develop as a consequence of students’ experience of educational, social, and cultural environments. The educational environment in particular is an important influence on how students view themselves as science learners and whether they feel supported to participate fully in the scientific community of the classroom.

Viewing the science classroom as a scientific community akin to communities in professional science is advantageous (although K-8 students are clearly not engaged in professional science). Science advances in large part through interactions among members of research communities as they test new ideas, solicit and provide feedback, articulate and evaluate emerging explanations, develop shared representations and models, and reach consensus. Likewise, participation in scientific practices in the classroom helps students advance their understanding of scientific argumentation and explanations; engage in the construction of scientific evidence, representations, and models; and reflect on how scientific knowledge is constructed.

To participate fully in the scientific practices in the classroom, students need to develop a shared understanding of the norms of participation in science. This includes social norms for constructing and presenting a scientific argument and engaging in scientific debates. It also includes habits of mind, such as adopting a critical stance, a willingness to ask questions and seek help, and developing a sense of appropriate trust and skepticism.

**Interconnections Among the Strands**

Interconnections among the strands in the process of learning are supported by research, although the strength of the research evidence varies across the strands. The cognitive research literatures support the value of teaching content in the context of the practices of science. For example, the knowledge factor, that is, the depth of one’s knowledge of the domain, has repeatedly been identified as a primary factor in the power or limitations of one’s scientific reasoning (Brewer and Samarapangavan, 1991; Brown, 1990; Carey, 1985; Chi, Feltovich, and Glaser, 1981; Goswami and Brown, 1989; see also the discussion in Chapter 5). Not surprisingly, both children’s and adults’ scientific reasoning tends to be strongest in domains in which their knowledge is strongest. Therefore, if the goal is to advance the leading edge of children’s scientific reasoning, their instruction needs to be grounded in contexts that also build on their relatively robust understanding of content. There is also mounting evidence that
knowledge of scientific explanations of the natural world is advanced through generating and evaluating scientific evidence. For example, instruction designed to engage students in model-based reasoning advances their conceptual understanding of natural phenomena (see, for example, Brown and Clement, 1989; Lehrer, et al., 2001; Stewart, Cartier, and Passmore, 2005; White, 1993; Wiser and Amin, 2001; see also the discussions in Chapter 4 and Chapter 9).

Evidence for links between Strands 3 and 4 and the other two strands is less robust, but emerging findings are compelling. Motivation, which is an element of Strand 4, clearly plays an important role in learning (see Chapter 7). Furthermore, instruction that makes the norms for participating in science explicit supports students’ ability to critique evidence and coordinate theory and evidence (Herrnkohl and Guerra, 1998; for further discussion, see Chapters 7 and 9).

Although we have teased apart aspects of understanding and learning to do science as four interrelated strands, we do not separate these as separate learning objectives in our treatment of the pedagogical literature. Indeed, there is evidence that while the strands can be assessed separately, students use them in concert when engaging in scientific tasks (Gotwals and Songer, 2006). Therefore, we contend that to help children develop conceptual understanding of natural systems in any deep way requires engaging them in scientific practices that incorporate all four strands to help them to build and apply conceptual models, as well as to understand science as a disciplinary way of knowing.

DEVELOPMENT, LEARNING AND INSTRUCTION

An important theme throughout this report is the complex interplay among development, learning and instruction, and the implications for science education. The evidence base for this report draws from several, mostly independent bodies of research, each emerging from different research traditions that operate within different theoretical frameworks. These frameworks differ in the relative emphasis placed on development versus learning and instruction. As a result, the different bodies of research often provide differing and somewhat conflicting pictures of children’s competence. Reconciling these visions of competence and understanding their implications for how to support science learning require careful consideration of the assumptions underlying both research and current practices in science education.

In science education, there has been a frequent assumption that development is a kind of inevitable unfolding and that one must simply wait until a child is cognitively “ready” for more abstract or theory-based forms of content. In other words, through maturation with age, children will achieve certain cognitive milestones naturally, with little direct intervention from adults. Many science educators and policy makers have assumed that the power and limitations of children’s scientific reasoning at different grade levels could be derived from the stages delineated in the cognitive developmental literature. In this view, “developmentally appropriate” education would thus require keeping instruction within these bounds.

There are significant problems with this assumption. First, it assumes that the power and limitations of children’s scientific thinking within an age band can be described and predicted by stage-defining criteria, with limited variability or change therein. As we show in the chapters in Part II, the cognitive developmental literature simply does not support this assumption. In the words of John Flavell, a seminal cognitive developmentalist (1994), “Virtually all contemporary developmentalists agree that cognitive development is not as general stage-like or grand stage-like as Piaget and most of the rest of the field once thought” (p. 574). The foundation of research
undermining a broad stage-like conception of cognitive development goes back at least three decades (see for example Wollman, Warren and Chen, 1982a and b among others).

In fact, variability in scientific reasoning within any age group is large, sometimes broader than the differences that separate contiguous age bands. In self-directed experimentation tasks, there are always some adults whose performance looks no better than that of the average child (Klahr, Fay, and Dunbar, 1993; Kuhn, Schauble, and Garcia-Mila, 1992; Kuhn, Garcia-Mila, Zohar, and Anderson, 1995; Schauble, 1996; see also the discussion in Chapter 5). Indeed, many adults never seem to master the heuristics for generating and interpreting evidence. Moreover, education, context, and domain expertise seem to play a strong role in whether and when these heuristics are appropriately used (Kuhn, 1991).

Stage-like conceptualizations of development also ignore the critical role of support and guidance by knowledgeable adults and peers. As noted in the National Research Council report *How People Learn* (1999), children need assistance to learn; building on their early capacities requires catalysts and mediation. Adults play a central role in “promoting children’s curiosity and persistence by directing their attention, structuring their experiences, supporting their learning attempts, and regulating the complexity and difficulty of levels of information for them” (p. xx). In the case of the science classroom, both teachers and peers can and must fill these critical roles. The power of schooling is its potential to make available other people, including adults and peers, to learn with; thought-provoking tasks; tools that both boost and shape thinking; and activity structures that encapsulate learning-supportive norms and processes.

Indeed, observational and historical studies of working scientists reaffirm the promise of looking closely at the ways in which environments support learning. These studies demonstrate that theory development and reasoning in science are components of an ensemble of activity that includes networks of participants and institutions (Latour, 1999); specialized ways of talking and writing (Bazerman, 1988); development of representations that render phenomena accessible, visualizable, and transportable (Gooding, 1989; Latour, 1990); and efforts to manage material contingency by making instruments, machines, and other contexts of observation (such as experimental apparatus). The alignment of instruments, measures, and theories is never entirely principled (e.g., Pickering, 1995), and, whether the scientists are professionals or school students, they wrestle with the relationships between these tools and the phenomena they are intended to capture.

A second major problem with assuming children’s learning will unfold without support is that what children are capable of doing without instruction may lag considerably behind what they are capable of doing with effective instruction. Further clouding the picture is that research on cognitive development may not be helpful in illuminating how instruction can advance children’s knowledge and skill. Often, studies in developmental psychology do not have an instructional component and therefore may be more informative about starting points than about children’s potential for developing scientific proficiency under effective instructional conditions.

For example, the idea that prior to middle school children are incapable of designing controlled experiments has been a ubiquitous assumption in the elementary school science community. This claim can be traced to Inhelder and Piaget’s (1958) influential study, *The Growth of Logical Thinking from Childhood to Adolescence*. Indeed the *Benchmarks for Scientific Literacy* (American Association for the Advancement of Science, 1993) included design of controlled experiments in their list of limitations of the scientific reasoning of third to fifth graders:
Research studies suggest that there are some limits on what to expect at this level of student intellectual development. One limit is that the design of carefully controlled experiments is still beyond most students in middle grades.

Consider the *Benchmarks*’ crucial—and unusual—caveat (p. 11):

> However, the studies say more about what students at this level do not learn in today’s schools than about what they might possibly learn if instruction were more effective.

Indeed, instructional studies have documented success at teaching controlled experimental design to children in this grade span (see Klahr and Nigam, 2004; Toth, Klahr, and Chen, 2000). As another example, consider the issue of reasoning about theory and evidence. In their delineation of the limitations on third to fifth graders’ scientific reasoning, the *Benchmarks* also claim that third to fifth graders “confuse theory (explanation) with evidence for it.” In accordance with this deficiency stance, most science curricula for young children avoid consideration of theory and evidence.

The developmental literature related to this fundamental aspect of scientific reasoning is more complex, with some studies in support of the *Benchmarks* stance and some studies suggesting greater competence. For example, Kuhn, Amsel, and O’Loughlin (1988) conclude that, in the preadolescent, theory and evidence “meld into a single representation as ‘the way things are’” (p. 221), whereas the research of Sodian, Zaitchek, and Carey (1991) indicates that, in some form and under some conditions, even preschoolers can make this distinction and reason accordingly.

Once again, the instructional literature indicates that children’s capabilities in this regard are to some degree amenable to instruction. The instructional design research literature provides an existence proof that elementary schoolchildren’s reasoning about theory and evidence in the context of doing science can be advanced under particular instructional conditions (see Smith, et al., 2000). In Chapter 5 we discuss evidence related to both of these examples.

The problem with reducing the power and limitations of children’s scientific reasoning to developmental stages is further undermined by the enduring challenges that many of these issues have posed to much older students and even to practicing scientists. For example, although one can read Inhelder and Piaget’s work (1958) as contending that an understanding of experimental control emerges with formal operational thought, we continue to train students well beyond adolescence in the logic of experimental design. Continuing with the examples used above, the differentiation of theory and evidence poses even more challenges. Indeed, the philosopher of science Stephen Toulmin (1972) has argued that observation and theory are at some level inevitably entangled; in his words, “the semantic and empirical elements are not so much wantonly confused as unavoidably fused” (p. 189). Delaying instruction until such a capability emerges through “development” cannot constitute a strategic tactic, as development alone cannot adequately elaborate the competence. Furthermore, there is mounting evidence that instruction can advance these capabilities as well as many others.

In short, young children have a broad repertoire of cognitive capacities directly related to many aspects of scientific practice, and it is problematic to view these as simply a product of cognitive development. Current research indicates that students do not go through general stages of cognitive development, and there are no “critical periods” for learning particular aspects of
science. Rather, cognitive capacities directly related to scientific practice usually do not fully develop in and of themselves apart from instruction, even in older children or adults. These capacities need to be nurtured, sustained, and elaborated in supportive learning environments that provide effective scaffolding and targeted as important through assessment practices.

Although there is much that is not understood about the relationships between development and learning, the evidence is clear that a student’s instructional history plays a critical role in her scientific knowledge, scientific reasoning, and readiness to do and learn more science. Components of the cognitive system (e.g., processing speed and capacity, strategies and heuristics, metacognition) certainly are factors that contribute to a student’s learning history, but so do other mechanisms that are manipulable by educators and constitute the “design tools” that a teacher can deploy to most directly affect science learning.
Strand 1: Know, use, and interpret scientific explanations of the natural world.

This strand includes acquiring facts and the conceptual structures that incorporate those facts and using these ideas productively to understand many phenomena in the natural world. This includes using those ideas to construct and refine explanations, arguments, or models of particular phenomena.

Strand 2: Generate and evaluate scientific evidence and explanations.

This strand encompasses the knowledge and skills needed to build and refine models based on evidence. This includes designing and analyzing empirical investigations and using empirical evidence to construct and defend arguments.

Strand 3: Understand the nature and development of scientific knowledge.

This strand focuses on students’ understanding of science as a way of knowing. Scientific knowledge is a particular kind of knowledge with its own sources, justifications and uncertainties. Students who understand scientific knowledge recognize that predictions or explanations can be revised on the basis of seeing new evidence or developing a new model.

Strand 4: Participate productively in scientific practices and discourse.

This strand includes students’ understanding of the norms of participating in science as well as their motivation and attitudes toward science. Students who see science as valuable and interesting tend to be good learners and participants in science. They believe that steady effort in understanding science pays off – not that some people understand science and other people never will. To engage productively in science, however, students need to understand how to participate in scientific debates, adopt a critical stance, and be willing to ask questions.

These strands of scientific proficiency represent learning goals for students as well as providing a broad framework for curriculum design. They address the knowledge and reasoning skills that students must eventually acquire to be considered fully proficient in science. They are also a means to that end: they are practices that students need to participate in and become fluent with in order to develop proficiency. Evidence to date indicates that in the process of achieving proficiency in science, the four strands are intertwined, so that advances in one strand support and advance those in another.

The committee thinks, and emerging evidence suggests, the development of proficiency is best supported when classrooms provide learning opportunities that interweave all four strands together in instruction.
REFERENCES


