Scientific Inquiry, Student Learning, and the Science Curriculum

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> *Different disciplines are organized differently and have different approaches to inquiry. For example, the evidence needed to support a set of historical claims is different from the evidence needed to prove a mathematical conjecture, and both of these differ from the evidence needed to test a scientific theory.* (Bransford, Brown, and Cocking 1999, 143)

The first sentence of this quotation from *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, and Cocking 1999) identifies the major theme of this chapter, which is that the conceptual structures of science disciplines and scientific inquiry should have a prominent place in school science programs. Such a view is consistent with the disciplines of science and supported by contemporary learning theory, but due to complexities such as the culture of schools, high-stakes assessments, and market-driven textbooks, it is not clearly evident in the science curriculum.

Relative to the science curriculum, in this chapter I use the term *scientific inquiry* in three distinct, but complementary ways: as science content that should be understood; as a set of cognitive abilities that students should develop; and as teaching methods that science teachers can use. The views I present here are consistent with those of the *National Science Education Standards* (NRC 1996) and *Inquiry and the National Science Education Standards* (NRC 2000).

The following discussion uses what we now understand about student learning to establish important links between scientific inquiry and the science curriculum. The chapter begins with a discussion of scientific inquiry. I then describe some related ideas from *How People Learn* and apply the discussion of student learning to our understanding of scientific inquiry and to the design of science curricula. I conclude with recommendations for practitioners.

Scientific Inquiry

To understand scientific inquiry and its place in science teaching, let us begin by reviewing some ideas about science and inquiry separately. This discussion sets the stage for later presentations of student learning and the design of science curricula.

Science

The achievements of science provide us interesting and important explanations about the world. Science does not and cannot tell us everything, but it does supply dependable knowledge that helps us understand the world in which we live. Scientific knowledge is greater than an accumulation of facts and information; indeed, it presents ideas and concepts that have explanatory power. That is, scientific knowledge often gives us some understanding of cause-and-effect relationships and the power to predict and control.

Although science supplies reliable knowledge, that knowledge often challenges our everyday ideas about reality. For nonscientists, it may be a challenge to understand that all substances consist of tiny particles held together by electrical forces; that the many materials in our world are made up of different arrangements of a surprisingly small number of particles; that some diseases are caused by microorganisms invisible to the naked eye; that heritable traits result from combinations of a chemical code; that all species have descended from common ancestors; and that huge plates on the Earth's surface are moving in somewhat predictable patterns.

These and other scientific ideas are expressed by terms such as the particulate nature of matter, the germ theory of disease, the genome and DNA, the evolution of life, and plate tectonics. Major ideas such as these and an unimaginable number of other concepts form a body of knowledge called science. Science teachers have the dual challenge of identifying which ideas are most important for students to learn and how to best teach those ideas, given the difference between what students currently know and understand about their world and the accepted scientific explanations about that same world. In educational terms, these two challenges can be summarized as those of curriculum and instruction—specifically, the content of the curriculum and the instructional approaches, strategies, and techniques of presenting that content. But, what about scientific inquiry?

Inquiry

Science is more than a body of knowledge. The concept of science as a way of explaining the world includes knowledge and explanation and the additional idea that science has particular ways or unique methods that scientists use. Indeed, science is more than a body of knowledge; what we know and even what we mean by scientific knowledge is a function of the processes by which scientists come to obtain that knowledge. What, to be specific, are the basic elements of those processes of scientific inquiry? In simple and direct summary, scientific inquiry uses processes such as observations and experiments that result in empirical evidence about the natural world. To be clear, it is not the authority of individuals, the dogma of religions, the doctrines of governments, or the power of private enterprise that carries weight in scientific explanations. Rather, it is the power of empirical evidence, critical analysis, and careful inference derived from observations and experiments that brings authority to scientific explanations. This is the particular and unique way that scientists explain the world.

The prevailing misconception of the public, most textbooks, and, unfortunately, some science teachers is that science is a systematic method that has variations of the following form: first, state a problem; second, form a hypothesis; third, perform an experiment; fourth, analyze data; and finally, present a conclusion. As presented in many science classes, the scientific method is systematic, precise, rigorous, and impersonal (Bauer 1992).

Some observations serve as counterpoints to the misconception of *a* scientific method. At the core of scientific inquiry, one finds observation, hypothesis, inference, test, and feedback. All of these processes serve the end of obtaining and using empirical evidence to help answer a scientific question. The scientist begins with an engaging question based on anomalous data, inconsistencies in a proposed explanation, or insights from observations. After some explorations, the scientist proposes a hypothesis from which predictions may be deduced through inference. Tests are designed to check the validity of the hypothesis. If the tests confirm the hypothesis the results are often published, providing feedback to scientists and the scientific community. Publishing the results is important whether the tests confirm or refute the hypothesis. Both types of feedback are important in science. If the results do not confirm the hypothesis, it may be altered, a new one proposed, or the scientists can stay with the original idea and try another investigation. Although the actual processes are not as clear as just stated, this summary provides insights for teachers and the representation of inquiry in the science curriculum and classroom.

The activity of scientific inquiry is not as tidy as the misconceived scientific method. It is, however, precise and methodologically appropriate to the discipline, the available technology, and the specific question being investigated. Data from the measurements and observations are theory-laden because the original question was guided by the knowledge and concepts of the scientist. After the original statement and testing of the hypothesis, scientists often report their results at a scientific meeting, thus providing initial explanations and methods to the community. Further work elaborates on the original ideas, and subsequent publications provide opportunities for scientists to evaluate the proposed explanation by replicating the original work or applying the explanation to new and different problems. Although ideal, this description at least hints at the complexity and the cyclical nature of scientific inquiry. The processes of observation, hypothesis, inference, test, and feedback continue all the time in a less than tidy manner.

Student Learning

This section establishes linkages between how students learn and scientific inquiry in the curriculum.

Learning Is a Basic, Adaptive Function of Humans

As this heading suggests, early in life, children begin perceiving regularity in objects, organisms, and their environment (Bransford, Brown, and Cocking 1999, xi). They engage in learning—making sense of their world. One can easily infer that children have a predisposition to learn, especially in particular domains such as biological and physical causality, number, space, time, and language. As children attempt to make sense of their world, they form explanations of phenomena that result in initial concepts that go on to form the basis of their scientific understanding of the world.

Learning Originates in Diverse Experiences

Although learning is a basic, adaptive human function and much of what children learn occurs through diverse spontaneous experiences and without formal instruction, when children's explanations are compared with scientific understanding of objects, organisms, and natural phenomena, the learners' explanations are often incomplete, inadequate, or inappropriate. To state the obvious, at some point these children become students, go to schools, and enter science classrooms. Important to this discussion is the fact that these students bring their current conceptions of biological and physical phenomena with them, and, more important, the students' current knowledge influences the learning process. From a science teacher's perspective, students' current knowledge can be viewed as naive, incorrect, or laden with misconceptions.

When students are confronted with new knowledge, they often maintain their current explanations in large part because those conceptions work. From the student's point of view they provide personal explanations of phenomena; in short, current concepts make sense of the world. So, the science teacher is confronted with students' current conceptions that mostly have developed through informal encounters with phenomena and the contrasting conceptions from the scientific body of knowledge. At the heart of this discussion of science teaching and student learning is the idea that new concepts develop from challenges to current conceptions, which may take the form of social interactions, encounters with new and different phenomena, personal reflection, specific questions from peers and parents, activities that are part of the science curriculum, and interactions with science teachers.

How Teachers Can Facilitate Student Learning

Teaching for conceptual change and greater scientific understanding requires systematic approaches designed to identify students' current conceptions; challenge the adequacy of current explanations; introduce scientific concepts that are intelligible, plausible, and helpful; and provide opportunities to apply new ideas in a familiar context.

Students' learning—that is, the formation of better scientific knowledge—may occur through the addition of knowledge to current concepts, creation of new concepts, or major modification of current concepts. In any instance, facilitating student learning requires time and diverse opportunities for students to construct understandings of the world.

Clearly, the contemporary view of how students learn implies content that is deeper than facts and information, a curriculum that is richer than reading, instruction that is longer than a lesson, and teaching that is more than telling. In the next section, I address some of the complex issues of applying a contemporary understanding of student learning to the practical issues of curriculum and instruction.

The Science Curriculum

This section addresses two features of the science curriculum—content and instruction. The discussions complement sections on scientific inquiry and student learning.

Content of the Science Curriculum

Recall the discussion on scientific inquiry. One theme of that discussion was knowledge—specifically, that scientific knowledge presents ideas and concepts in an organized and systematic way. There is, to use Jerome Bruner's phrase from the 1960s, "structure to the disciplines." This theme has a parallel in the research on expert/novice learners. One finding has implications for this discussion. In summarizing the question of how experts' knowledge is organized and how this affects their abilities to understand and represent problems, Bransford, Brown, and Cocking (1999) had this to say:

> *Their knowledge is not simply a list of facts and formulas that are relevant to their domain; instead, their knowledge is organized around core concepts or "big ideas" that guide their thinking about their domains.* (24)

Most science curricula used in K–12 education tend to overemphasize facts and information while underemphasizing major concepts and "big ideas." The *National Science Education Standards* (NRC 1996) provide one example of a set of recommendations that would emphasize major conceptual ideas and fundamental concepts associated with those ideas for grades K–4, 5–8, and 9–12. One also should note that the recommendation to emphasize major concepts is consistent with findings from the Third International Mathematics and Science Study (TIMSS) (Schmidt, McKnight, and Raizen 1997; Schmidt et al. 1999).

Organization of Content

Although the *National Science Education Standards* (NRC 1996) do *not* represent a curriculum, the content standards illustrate important features such as emphasis on major ideas, links to meaningful experiences, and uses that are developmentally appropriate for the learner. For example, Table 1 illustrates content standards that might be used as major conceptual organizers in a science curriculum.

Table 1. Major Conceptual Organizers from the *National Science Education Standards*

	Grades K–4	Grades 5–8	Grades 9–12
Physical Science (matter)	Properties of objects and materials	Properties and changes of properties of matter	Structure of atoms Structure and properties of matter
(energy)	Light, heat, electricity, and magnetism	Transfer of energy	Conservation of energy and increase in disorders
Life Science (evolution)	Characteristics of organisms	Diversity and adaptations of organisms	Biological evolution
(genetics)	Life cycles of organisms	Reproduction and heredity	Molecular basis of heredity
Earth/Space Sciences (Earth systems)	Properties of Earth materials	Structures of the Earth system	Origin and evolution of the Earth system
(astronomy)	Objects in the sky	Earth in the solar system	Origin and evolution of the universe

The organization of content illustrated in Table 1 would support learning for understanding and making sense of experiences. This "progressive formalization" begins with the informal ideas that students bring to school in the lower grades (K–4) and gradually helps them develop and perhaps restructure those ideas into formal science concepts in the upper grades (9–12). Content in a curriculum would be organized so students build scientific understanding and abilities of inquiry in a gradual and structured manner during their school years.

Use of the *National Science Education Standards* and the organization of content, such as just illustrated, reduces the emphasis on facts, increases the emphasis on major ideas, and provides focus, coherence, and rigor to the science curriculum. From a larger view of school science programs, it gives students time to confront and reconstruct concepts that form the structure of science disciplines. This approach aligns with prior discussions of a knowledge base for scientific inquiry, is supported from the perspective of student learning, and provides a positive response to criticisms that the U.S. science curriculum lacks focus, coherence, and rigor (Schmidt, McKnight, and Raizen 1997; NRC 1999).

I conclude this section by pointing out that some curriculum materials that align with the aforementioned characteristics do exist, although they are not widely used. For example, the BSCS program *BSCS Science T.R.A.C.S.* at the elementary level and *BSCS Biology: A Human Approach* for high school life sciences are two such programs. Other National Science Foundation (NSF)–supported programs such as *Active Physics, Chemistry in the Community,* and *Earth Science in the Community* also align with national standards. (See *Profiles in Science: A Guide to NSF-Funded High School Instructional Materials*, BSCS 2001).

Effective Science Instruction

Science teaching is a complex process that, at best, combines an understanding of students, science, and the educational environment as teachers make long-term decisions about the curriculum and instantaneous responses to classroom situations. This complexity notwithstanding, based on the results of research on learning, there are some understandings and practices that will make science instruction more effective.

An Instructional Model

Children's curiosity leads to their informed inquiries into many aspects of the world. The natural inquiry of children and the more formal problem solving of adults often follow a pattern of initial engagement, exploration of alternatives, formation of an explanation, use of the explanation, and evaluation of the explanation based on its efficacy and responses from others. I will note here that this process of natural inquiry is quite similar to the more formal processes of scientific inquiry, as described in prior sections. The parallel is intended, and in fact, extends to the discussion of student learning. I quote from a section on knowledge-centered environments in *How People Learn.*

> *An alternative to simply progressing through a series of exercises that derive from a scope and sequence chart is to expose students to the major features of a subject domain as they arise naturally in problem situations. Activities can be structured so that students are able to explore, explain, extend, and evaluate their progress. Ideas are best introduced when students see a need or a reason for their use—this helps them see relevant uses of knowledge to make sense of what they are learning.* (Bransford, Brown, and Cocking 1999, 127)

This quotation directs our attention to the research-based recommendation that activities be structured to allow students to explore, explain, extend, and evaluate their progress. Note the suggestion that activities are structured to encourage conceptual change and a progressive re-forming of their ideas. This structured approach to teaching is further justified by the fact that the opportunities and time allow students to see relevant uses and make sense of their learning experiences. This discussion leads to support for an instructional model, specifically the BSCS 5E model I have advocated for over two decades (see, e.g., the structure of chapters in Bybee and Sund 1982; Chapter 8, "Improving Instruction," in Bybee 1997). Since the late 1980s the 5E model also has been used extensively in BSCS programs. Table 2 summarizes the 5E model.

Table 2. The BSCS 5E Instructional Model

ENGAGE

Engage lessons provide the opportunity for science teachers to identify students' current concepts and misconceptions. Although provided by a teacher or structured by curriculum materials, these activities introduce major ideas of science in problem situations. The theme here might be—*how do I explain this situation?*

EXPLORE

Explore lessons provide a common set of experiences for students and opportunities for them to "test" their ideas with their own experiences and those of peers and the science teacher. The theme for this phase is—*how do my exploration and explanation of experiences compare with others?* Students have the opportunity to compare ideas that identify inadequacies of current concepts. Here, the theme is—*how does one challenge misconceptions?*

EXPLAIN

Explain lessons provide opportunities for students to use their previous experiences to recognize misconceptions and to begin making conceptual sense of the activities through the construction of new ideas and understandings. This stage also allows for the introduction of formal language, scientific terms, and content information that makes students' previous experiences easier to describe and explain. The theme is—*this is a scientific explanation.*

ELABORATE

Elaborate lessons apply or extend the student's developing concepts in new activities and relate their previous experiences to the current activities. Now the theme is—*how does the new explanation work in a different situation?*

EVALUATE

Evaluate lessons can serve as a summative assessment of what students know and can do at this point. Students confront a new activity that requires the understandings and abilities developed in previous activities. The final theme is—*how do students understand and apply scientific concepts and abilities?*

The BSCS 5E model was initially based on and elaborated earlier instructional approaches (Bybee 1997). It was designed as an instructional sequence primarily for use at the activity level. Although not originally based on scientific inquiry as discussed earlier, general connections seem evident. Likewise, connections with classroom inquiry and the general theme of teaching science as inquiry appear to be clear.

Linking Inquiry and Instruction

The BSCS 5E model takes a curricular perspective, in particular a view that incorporates what we know about how students learn and accommodates many everyday requirements of science teaching. For example, the instructional model can be used

Table 3. Essential Features of Classroom Inquiry and Their Variations along Two Continua

More	**Amount of Learner Self-Direction**			**Less**
Less	**Amount of Direction from Teacher or Written Material**			**More**
Learner **engages** in scientifically oriented questions	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by teacher, materials, or other source	Learner engages in question provided by teacher, materials, or other source
Learner gives priority to **evidence** in responding to questions	Learner determines what constitutes evidence and collects it	Learner directed to collect certain data	Learner given data and asked to analyze	Learner given data and told how to analyze
Learner formulates **explanations** from evidence	Learner formulates explanation after summarizing evidence	Learner guided in process of formulating explanations from evidence	Learner given possible ways to use evidence to formulate explanation	Learner provided with evidence
Learner connects explanations to scientific **knowledge**	Learner independently examines other resources and forms the links to explanations	Learner directed toward areas and sources of scientific knowledge	Learner given possible connections	Learner given steps and procedures for communication
Learner **communicates** and **justifies** explanations	Learner forms reasonable and logical argument to communicate explanations	Learner coached in development of communication	Learner provided broad guidelines to use to sharpen communication	Learner given connections to scientific knowledge

Adapted from National Research Council (NRC). 2000. *Inquiry and the National Science Education Standards.* Washington, DC: National Academy Press.

with thirty or more students; it also incorporates laboratory investigations, educational technology, cooperative learning, and other strategies. Classroom inquiry has five essential features as described in *Inquiry and the National Science Education Standards* (NRC 2000). Those features are summarized as follows:

1. Learners ENGAGE in scientifically oriented questions.
2. Learners give priority to EVIDENCE in responding to questions.
3. Learners formulate EXPLANATIONS from evidence.
4. Learners connect explanations to scientific KNOWLEDGE.
5. Learners COMMUNICATE and JUSTIFY explanations.

Although not a direct and a one-to-one correspondence, the connections among scientific inquiry, student learning, and the 5E model should be evident. Table 3 presents these essential features and variations of the features as they may appear in science classrooms.

From the perspective of teacher direction and student self-direction, few, if any, students will demonstrate the essential features of inquiry when they first experience scientific investigations. Because of this, science teachers will find practical value and support for their work in the variations of these essential features as they implement a curriculum, teach science as inquiry, and work toward a professional goal to further students' understanding of science.

Conclusion

This chapter uses student learning, specifically the National Research Council's report *How People Learn*, as a bridge connecting scientific inquiry and curriculum with instruction in science. Use of content standards from the *National Science Education Standards* and the 5E instructional model were presented as practical ways for science teachers to incorporate scientific inquiry and apply our understanding of student learning. Teaching science as inquiry provides opportunities for students to learn fundamental concepts, develop the abilities of inquiry, and acquire an understanding of science.

Specifically, the following recommendations emerge from this chapter. Practitioners will establish connections between scientific inquiry and enhance student learning when they:

- Focus on core content, for example, the fundamental concepts articulated in the *National Science Education Standards*.
- Use an instructional sequence that supports what we know about student learning, for example, the BSCS 5E model.
- Create knowledge-centered learning environments that incorporate the essential features of classroom inquiry, for example, those described in *Inquiry and the National Science Education Standards* (NRC 2000).

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THE LEARNING CYCLE MODEL

"Class, you'll notice that I've given each lab group a D-cell battery and battery holder, a flashlight bulb, and a piece of insulated wire," Mrs. Smith began. "Using these materials, I'd like you to light the bulb." As the students succeeded in lighting their bulbs, she asked them to explain how they had done it.

After students had shared ideas about their bulb systems, Mrs. Smith introduced the terms in their science textbook *current* and *open* and *closed circuit*. She had students read about these terms and then discussed the reading with them.

Finally the students applied their knowledge of electric circuits to a new situation. Each group connected a switch and two new pieces of wire to their bulb system and created a closed circuit. Mrs. Smith asked them to describe how the switch worked, and to try to explain how the light switches in the classroom turn the overhead light on and off.

The steps in Mrs. Smith's method may seem to be in reverse, but she was practicing a teaching strategy called the Learning Cycle to develop students' understanding of open and closed circuits. In the Learning Cycle, students first engage in hands-on activities to familiarize them with the concepts and relationships <u>before</u> being introduced to new terms, reading text material, graphing or otherwise analyzing their observational data. Next, concepts are developed based on experiences acquired from exploratory activities. It appears that students are more receptive to understanding a concept if they have first engaged directly in a concrete experience which has raised a question in their minds. It is this need for further understanding that urges them to enter in to the reevaluating old or building new concepts. The third part of the Learning Cycle features an application activity where the concept is used in a slightly different setting than was originally developed, thus giving them a chance to more fully understand the concept in terms of a wider frame of reference.

The Learning Cycle is anchored in a thorough understanding of learning theory. Although Robert Karplus is generally viewed as the "father" of this model of instruction, its roots go back to the developmental learning theories of Piaget. A slightly more theoretical discussion of the model is provided below in more psychological terms.

Piaget (1964) identified four major factors which he believes relevant to the development of cognitive reasoning abilities. These factors are

1 <u>Maturation</u> - students must be biologically mature and physically developed and therefore capable of operating physically in their environment.
2. <u>Experience</u> - students past concrete experience and the ability to recall these experiences are critical for further development. Piaget outlines two types of experience: <u>Physical Experience</u> (drawn directly from objects) and <u>Logical-Mathematical Experience</u> (drawn by actions which affect objects).
3. <u>Social Communication</u> - students must be capable of communicating information via written and oral language.
4. <u>Equilibration</u> - for cognitive growth, students must be supplied a situation of cognitive challenge where their existing mental operations are not adequate. The accommodative process (called equilibration) by which the student deals with this new information will result in cognitive growth.

A translation of this Piagetian theory into a workable model for designing learning experience should incorporate each of these factors (Campbell, 1977). When applied to adolescent students, factors one and three are probably not as important as factors two and four. Piaget himself stresses the interdependence of all four factors but suggests factor two and its proper relation to factor four are fundamental to learning and development.

The Learning Cycle Model, as originally conceived by Robert Karplus in the 1960s, can be divided into three major segments: **Exploration, Concept Invention**, and **Concept Extension**. The following is an overview illustrating the important general characteristics of each phase.

Exploration - Following a brief statement of topic and direction, students are encouraged to learn through their own experience. Activities may be supplied by the instructor which will help the students recall (and share) past concrete experiences or assimilate new concrete experiences helpful for later invention and/or extension activities. During this activity the students receive only minimal guidance from their instruction and explore new ideas spontaneously.

1. This phase of the Learning Cycle provides students with reinforcement of previous concrete experience and/or introduces them to new concrete experience related to the intended outcome objectives.
2. The activity allows for "open-ended" considerations, encouraging students to allow concrete experiences to evoke non-concrete ideas as possible relevant factors.
3. During the exploration activity the instructor supplies encouragement and hits and/or suggestions to maintain an appropriate level of disequilibrium.
4. This activity provides the instructor information concerning the students ability to deal with the concepts and/or skills being introduced. In addition, the students will deal the reasoning skills which they may evoke in search for the solution to a problem.

Concept Invention - In this phase, the concrete experience provided in the exploration is used as the basis for generalizing a concept, for introducing a principle, or for providing an extension of students' skill or reasoning. Student and instructor roles in this activity may vary depending upon the nature of the content. Generally, students should be asked to "invent" part or all of the relationship for themselves with the instructor supplying encouragement and guidance when needed. this procedure allows for students to "self-regulate" and therefore move toward equilibrium with the concepts introduced.

1. During the invention activity students are encouraged to formulate relationships which generalize their ideas and concrete experiences.
2. The instructor acts as a mediator in assisting students to formulate these relationships so as to be consistent with the outcome objectives.

Concept Extension - the extension or application phase of the Learning Cycle allows each student an opportunity to directly apply the concept or skill learned during the invention activity. This activity allows additional time for accommodation required by students needing more time for equilibration. It also provides additional equilibrating experiences for students who have already accommodated the concepts introduced.

1. To begin the extension activity, students and instructors interact in planning an activity for apply the "invented" concept and/or skill in a situation relevant to the instructional objectives.
2. Finally, students are asked to complete the designed activity to the satisfaction of the instructor. While this extending activity allows students to directly apply the invented concept to a new situation, the broadening nature of the activity provides for further equilibration of new cognitive abilities.

Although the Learning Cycle allows each student the opportunity to think for himself, the instructor must be an ever present "overseer" of the activity, and by providing probing questions, hints, and encouragement keep the activity going. Yet the instructor must guard against over playing his role as director and planner. It is here that many of you who implement the Learning Cycle for the first time may have trouble. Traditionally, the teacher has been the "fount of knowledge" in both the classroom and laboratory settings. We have been the ones with all the answers and with the "best way" to get the results that we want our students to use. Our role changes when using the Learning Cycle. We are now facilitators. Yes, we can still be a source of knowledge, but it is not volunteered. Rather, we consultants and cheerleaders instead of authority figures that students follow in lockstep.