

## **Part 1**

# Why Inquiry?



## Some Thoughts of a Scientist On Inquiry

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**W**hat do we mean when we emphasize that much of science should be taught as inquiry?

It is certainly easy to recognize another, much more familiar type of science teaching, in which the teacher provides the student with a large set of science facts along with the many special science words that are needed to describe them. In the worst case, a teacher of this type of science is assuming that education consists of filling a student's head with a huge set of word associations —such as mitochondria with “powerhouse of the cell,” DNA with “genetic material,” or motion with “kinetic energy.” This would seem to make preparation for life nearly indistinguishable from the preparation for a quiz show, or the game of trivial pursuit.

If education is simply the imparting of information, science, history, and literature become nearly indistinguishable forms of human endeavor, each with a set of information to be stored in one's head. But most students are not interested in being quiz show participants. Failing to see how this type of knowledge will be useful to them, they often lack motivation for this type of “school learning.” Even more important to me is the tremendous opportunity that is being missed to use the teaching of science to provide students with the skills of problem solving, communication, and general thinking that they will need to be effective workers and citizens in the 21st century.

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### SOME EXAMPLES OF INQUIRY

If I think back to those aspects of my early education that have meant the most to me, I associate all of them with struggling to achieve an understanding that required my own initiative: writing a long report on “The Farm Problem” in seventh grade in which I was forced to explain why our government was paying farmers for not growing a crop; being assigned to explain to my eighth-grade class how a television set works; or in ninth grade grappling with the books on spectroscopy in the Chicago public library in order to prepare a report on its uses in chemistry.

What I mean by teaching science as inquiry is, at a minimum allowing students to conceptualize a problem that was solved by a scientific discovery, and then forcing them to wrestle with possible answers to the problem before they are told the answer. To take an example from my field of cell biology: the membrane that surrounds each cell must have the property of selective permeability—letting foodstuffs like sugars pass inward and wastes like carbon dioxide pass out, while keeping the many large molecules that form the cell tightly inside. What kind of material could this membrane be made of, so that it would have these properties and yet be readily able to expand without leaking as the cell grows? Only after contending with this puzzle for a while will most students be able to experience the pleasure that should result when the mechanism that nature derived for enclosing a cell is illustrated and explained. Classroom research with long-term followup shows that students are more likely to retain the information that they obtain in this way—incorporating it permanently into their view of the world (see, for example, G. Nuthall & A. Alton-Lee, 1995).

But there is much more. Along with science knowledge, we want students to acquire some of the reasoning and procedural skills of scientists, as well as a clear understanding of the nature of science as a distinct type of human endeavor. For some aspects of science knowledge that are more accessible to direct study than is the nature of the cell membrane, we therefore want students not only to struggle with possible answers to problems, but also to suggest and carry out simple experiments that test some of their ideas. One of the skills we would like all students to acquire through their science education is the ability to explore the natural world effectively by changing one variable at a time, keeping everything else constant. This is not only the way that scientists discover which properties in our surroundings depend on other properties; it also represents a powerful general strategy for solving many of the problems that are encountered in the workplace, as well as in everyday life in our society.

As an example, a set of fifth-grade science lessons developed by the Lawrence Hall of Science concentrates on giving students extensive experience in manipulating systems with variables. In this case, eight weeks of lessons come in a box along with a teacher's guide with instructions on how to teach with these materials (1993). The class starts by working in groups of four to construct a pendulum from string, tape, and washers. After each group counts the number of swings of its pendulum in 15 seconds with results that vary among pendulums, the class is led to suggest further trials that eventually trace the source of this variability to differences in the length of the string. Hanging the pendulums with different swing counts on a board in the front of the room makes clear the regular relation between pendulum length and swing rate, allowing each group to construct a pendulum with a predictable number of swing counts. This then leads to graphing as a means of storing the data for reuse in future pendulum constructions. A teacher could also exploit this particular two-week science lesson to acquaint students with the history of time keeping, emphasizing the many changes in society that ensued once it became possible to divide the day and night into reliable time intervals through the invention of pendulum clocks (Boorstin, 1985).

Contrast this science lesson with more traditional instruction about pendulums, in which the teacher does all of the talking and demonstrating, the students displaying their knowledge about which variables—length, weight, starting swing height—affect swing rate by filling in a series of blanks on a ditto sheet. A year later, the students are unlikely to remember anything at all about pendulums; nor have they gained the general skills that are the most important goal of the hands-on experience: recognition of the power of changing one variable at a time; the ability to produce graphs to store and recall information; the realization that everyone can carry out interesting experiments with everyday materials.

## THE IMPORTANCE OF MOTIVATION

Why are we so often fascinated to watch a live sporting event, sitting on the edge of our seats as the tension builds in a close contest? And why, in comparison, do we have so little interest in watching the same event replayed on television, where the final outcome is already known? I conclude that human beings like to confront the unknown. Other types of games demonstrate that we also like challenging puzzles. Solving puzzles calls for playing out the consequences of a gamble—following particular pathways selected by our free will. Properly constructed, inquiry in education motivates students for the

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same reasons—it confronts them with an unknown puzzle, which can be solved only by a process that involves risk taking.

I use this conjecture to explain why essentially every scientist whom I know remembers being utterly bored by the cookbook laboratories common to college biology, chemistry, and physics courses. My own experience is typical. After two years as a premedical student, I could stand these required labs no longer. I therefore petitioned out of the laboratory attached to the physical chemistry course at Harvard, seizing on an opportunity to spend afternoons in my tutor's research laboratory. This experience was so completely different that it soon caused me to forget about applying to medical school. Within a year I had decided to go to graduate school in biophysics and biochemistry, in preparation for a career in science.

Extensive studies have been carried out that examine the motivation and value systems of the students in American schools. One of these extended over a period of 10 years and involved 20,000 middle-class Americans in grades 6 to 10. The results have been published in the academic literature, but they were also presented for public consumption in a book (Steinberg et al., 1997). The results are extremely distressing to those, like myself, who believe that the future of this nation will depend primarily on the quality of the education that our young people are receiving. Fully 40% of the students studied were categorized as “disengaged” from learning. These students attended school regularly, but did not think that any studying that they did there was relevant or important. And only 15% of all students said that their friends would think better of them if they did well in their academic studies.

Who is to blame for this state of affairs? Some of the onus must be on parents who pay too little attention to what their adolescents are doing in school. But having been a parent who was once frightened by the overwhelming influence of peer attitudes on my own children's values, I have to see this as a much more complex issue. What are our children being taught in grades 6 to 10? Would we ourselves find the curriculum interesting and motivating? Speaking as a scientist who has examined what is taught as science in grades 6 to 10, for most schools I must answer with a resounding no! In general, the curriculum is built around dull, vocabulary-laden textbooks, which are impossible to understand in any real sense of the word. Most of these textbooks have clearly been written by people who either lack any deep understanding of the material being taught, or are constrained by their publishers from making their book interesting to study or to read. In such a situation, is it any wonder that school becomes an institution in which peer values discourage academic performance?

## A MAJOR CHALLENGE FOR OUR SCHOOLS

Inquiry is in part a state of mind, and in part a skill that must be learned from experience. The state of mind is inquisitiveness—having the curiosity to ask “Why” and “How.” The good news is that young children are naturally curious. But if their incessant “Why” is dismissed by adults as silly and uninteresting, given only a perfunctory “just because” or “I don’t know,” children can lose the gift of curiosity that they began with, and develop into passive, unquestioning adults. Visit any second-grade classroom and you will generally find a room full of energy and excitement, with kids eager to make new observations and to try to figure things out. What a contrast with our eighth graders, who so often seem bored and disengaged from learning and from school.

The challenge is to create an educational system that exploits the tremendous curiosity that children initially bring to school, so as to maintain their motivation for learning—not only during their school years, but also throughout their lifetimes. Above all, we need to convince both teachers and parents of the importance of giving encouraging and supportive answers to the many “Why” questions, thereby showing that we value inquisitiveness. I am reminded of the profound effect that Richard Feynman’s father had on his development as a scientist. As Feynman (1998) tells it:

One kid says to me, “See that bird? What kind of bird is that?”

I said, “I haven’t the slightest idea what kind of a bird it is.”

He says, “It’s a brown-throated thrush. Your father doesn’t teach you anything!”

But it was the opposite. He had already taught me: “See that bird?” he says. “It’s a Spencer’s warbler.” (I knew he didn’t know the real name.) “Well, in Italian, it’s a *Chutto Lapittida*. In Chinese, it’s a *Chung-long-tah*, and in Japanese, it’s a *Katano Tekeda*. You can know the name of that bird in all the languages of the world, but when you’re finished, you’ll know absolutely nothing whatever about the bird. You’ll only know about humans in different places, and what they call the bird. So let’s look at the bird and see what it’s *doing*—that’s what counts.” (I learned very early the difference between knowing the name of something and knowing something.)

He said, “For example, look: the bird pecks at its feathers all the time. See it walking around, pecking at its feathers?”

“Yeah.”

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He says, “Why do you think birds peck at their feathers?”

I said, “Well, maybe they mess up their feathers when they fly, so they’re pecking them in order to straighten them out.”

“All right,” he says. “If that were the case, then they would peck a lot just after they’ve been flying. Then, after they’ve been on the ground for a while, they wouldn’t peck so much any more—you know what I mean?”

“Yeah.”

He says, “Let’s look and see if they peck more just after they land.”

It wasn’t hard to tell: there was not much difference between the birds that had been walking around a bit and those that had just landed. So I said, “I give up. Why does a bird peck at its feathers?”

“Because there are lice bothering it,” he says. “The lice eat flakes of protein that come off its feathers.”

He continued, “Each louse has some waxy stuff on its legs, and little mites eat that. The mites don’t digest it perfectly, so they emit from their rear ends a sugar-like material, in which bacteria grow.”

Finally he says, “So you see, everywhere there’s a source of food, there’s some form of life that finds it.”

Now, I knew that it may not have been exactly a louse, that it might not be exactly true that the louse’s legs have mites. That story was probably incorrect in *detail*, but what he was telling me was right in *principle*.  
(pp. 13-15)

Very few children are fortunate enough to have a parent like Feynman’s. Much of the responsibility for nurturing the state of mind needed to be an inquiring adult therefore falls to our schools. Maintaining children’s initial curiosity about the world requires making them confident that they can use the methods of inquiry to find answers for their questions. This self-confidence can be developed in only one way: from a string of actual successes. It is not enough to encourage students to inquire. They must also have many opportunities to obtain the diverse set of skills needed for repeated success in such experiences.

For our schools, we should seek a curriculum that begins in kindergarten and increases in difficulty so as to provide, at each grade level, challenges appropriate to the students' age. This curriculum should focus on student and class inquiry, rather than on the memorization and regurgitation of facts. At each grade level, the inquiries need to be carefully designed to present students with challenges that are difficult enough to seem almost inaccessible at first, but which allow at least partial success for most students. We want students to see clearly that, as they acquire the tools and habits of inquiry, they are becoming more and more proficient in dealing with the world around them. School then becomes a highly relevant place for students: a place where they recognize that they are learning important skills for their life *outside* of school.

## A MAJOR CHALLENGE FOR SCIENTISTS

Instead of merely blaming others for the current state of science education, we scientists need to confront our own failings. Why do the same scientists who remember with distaste their own college laboratory experiences continue to run their own college students through the same type of completely predictable, recipe-driven laboratory exercises that once bored them? I remain mystified, with no good answer. But I am trying to encourage my former university colleagues to think deeply about this question and act accordingly. Perhaps they can think of no alternative. If so, they should spend a few hours examining one of the outstanding science modules based on inquiry that have been developed for elementary schools (see, for example, *Science and Technology for Children*, a joint project of the National Academy of Sciences (NAS) and the Smithsonian Institution at <http://www.si.edu/nsrc>). I see no reason why inexpensive, commercially available college laboratory modules could not be produced that are modeled after such outstanding elementary school examples. A project with this aim could stimulate a badly needed rethinking of what our introductory college science laboratories should be like, and what purposes they are supposed to serve.

We scientists also have a great deal of work to do in addressing the nature of our introductory college science courses. Where in a typical Biology 1 college course is the science as inquiry that is recommended for K-12 science classes in the *National Science Education Standards* (National Research Council [NRC], 1996)? These courses generally attempt to cover all of biology in a single year, a task that becomes ever more impossible with every passing year, as the amount of new knowledge explodes. Yet old habits die hard, and most Biology 1 courses are still given as a fact-laden rush of lectures. These lectures leave no time for

inquiry: they even fail to provide students with any sense of what science is, or why science as a way of knowing has been so successful in improving our understanding of the natural world and our ability to manipulate it for human benefit. (For attempts to change this situation, see *Science Teaching Reconsidered*, [NRC, 1997] and *Teaching Evolution and the Nature of Science* [NAS, 1998]).

## ON BECOMING A SCIENTIST

Very few students of science will go on to become professional scientists. That is not the primary purpose of current science education reforms. But I am convinced, both by my personal experience and from my extensive interactions with students, that the desired changes in our nation's K-16 science education will also contribute to the production of better scientists. If we stress understanding in addition to knowledge, and if we use inquiry methods that generate scientific habits of mind, students will not need to work in a research laboratory to appreciate the excitement of a life in science. And students with superb memorization skills, who often do well in our current science classes, will not be misled into believing that excelling in science requires the same skills as doing well on an exam.

If young people with outstanding scientific potential are never exposed to scientific inquiry and never given any illustration of what doing science is like, how can they think meaningfully about the possibility of a scientific career? But here we face another conundrum. Because of the way that we teach science in our colleges and universities, most science teachers in our schools—including former science majors—have never participated in scientific inquiry themselves. Is it any wonder that so many teachers are unable to teach their children according to the recommendations of the *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) or the *National Science Education Standards* (NRC, 1996), even when supplied with outstanding hands-on science curricula?

Faced with this dilemma, some suggest that we retreat from our ambitious education goals and settle for what all teachers can teach—science as memorization, evaluated by multiple-choice examinations that stress the recall of word associations. But I am convinced that we need not settle for a second-class education for our children, and that indeed we cannot do so without giving up our hope of remaining the world's leading nation.

As president of the National Academy of Sciences for the past six years, I have been trying to convince my many scientific colleagues across the United States that they must stop being part of the problem and instead become part of the answer. Our nation is blessed with the world's strongest scientific and engineering community, and very few places in our nation lack experts in scientific inquiry. These working scientists and engineers need to connect intimately to our local K-12 education systems—as volunteers to help teachers and school districts, as providers of professional development, and as a stable local political force advocating for a new type of science education (see <http://www.nas.edu/rise>).

But we need something more. The necessity of hiring two million of our nation's 3.5 million teachers in the next decade (National Commission on Teaching and America's Future, 1996), coupled with the imminent retirement of the bolus of science teachers and leaders who were produced in the era immediately after Sputnik, requires the entry of a new generation of talented scientists into our nation's K-12 teaching corps. Ideally, they would become teachers with a deep understanding of both science and inquiry—and form a natural bridge between the culture of science and that of the schools.

In the abstract, there would seem to be little chance of finding large numbers of such talented people and moving them into our K-12 school systems. But these are not normal times for scientists. Over the course of the past 40 years, the flourishing scientific enterprise in the United States has developed a dependence on an ever-increasing influx of young trainees who, serving as graduate students and postdoctoral fellows, perform most of the research that is carried out in our universities and publicly funded research institutes. As these people have aged and formed their own laboratories, they too have wanted young trainees to staff their laboratories. Because most professors will produce many potential new professors over the course of their careers, this system cannot be sustained over the long run unless either the number of science faculty at universities keeps increasing, or many other types of positions are developed in our society for Ph.D. scientists. Such concerns, triggered by an increasing frustration expressed by the young scientists looking for traditional employment, caused the National Research Council to carry out a major study to track the current career paths of life scientists (1998). The findings reveal that, over the past decade, the number of Ph.D.s awarded in the life sciences has been increasing at a rate of about 4% a year, whereas the number of research positions for them in universities, research institutes, and industry has been increasing at only about 3% a year. The result is a widening ever-increasing pool of poorly paid

postdoctoral researchers who are spending longer and longer times in temporary positions.

From the twenty thousand or so present postdoctoral researchers in the life sciences and an expected growth in their numbers, could we generate a new generation of outstanding science teachers at the K-12 level who really understand inquiry? My own contacts with these young scientists have convinced me that many of them are willing to try. But they will do so only if efficient training programs become available to provide them with the additional skills that they need to teach well, if we in the scientific community demonstrate our support for their career change and continue to treat them as colleagues, and if school systems are willing to hire and support them once they have been trained.

I view the current situation as a terrific, one-time opportunity for scientists who want to help reinvigorate our school systems. With the proper preparation and support, these scientists can immediately introduce inquiry into the curriculum, and they can help generate new types of professional development experiences for other teachers in their schools. The National Academy of Sciences has begun to focus on this critical issue, which I believe to be of utmost importance for the future of science, as well as for the future of our schools.

## REFERENCES

- American Association for the Advancement of Science. 1993.  
*Benchmarks for science literacy*. New York: Oxford University Press.
- Boorstin, D.J. 1985. *The discoverers*. New York: Random House.
- Feynman, R.P. 1998. *The making of a scientist, What do you care what other people think?* New York: Bantam Books.
- Lawrence Hall of Science. 1993. Variables. Module in *Full option science system*. Chicago: Encyclopedia Britannica Educational Corp.
- National Commission on Teaching and America's Future. 1996.  
*What matters most: Teaching for America's future*. New York: Author.

- National Academy of Sciences. 1998. *Teaching evolution and the nature of science*. Washington, DC: National Academy Press.
- National Research Council. 1996. *National science education standards*. Washington, DC: National Academy Press.
- National Research Council. 1997. *Science teaching reconsidered*. Washington, DC: National Academy Press.
- National Research Council. 1998. *Trends in the early careers of life scientists*. Washington, DC: National Academy Press.
- Nuthall, G., and A. Alton-Lee. 1995. Assessing classroom learning: How students use their knowledge and experience to answer classroom achievement test questions in science and social studies. *American Educational Research Journal* 31: 185-223.
- Steinberg, L., B. Brown, and S. Dornbusch. 1997. *Beyond the classroom*. Cambridge, MA: Touchstone Books.

## The Three Faces of Inquiry

Gerald F. Wheeler

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The word “inquiry” comes up often in conversations about reform in science education. But “inquiry” is an elastic word, stretched and twisted to fit people’s differing worldviews. Inquiry itself a core tenet of the standards, and the ambiguity surrounding it is a threat to reform efforts.

### THE FIRST FACE ENGAGES STUDENTS

One image of inquiry has a classroom with children engaged in a hands-on activity. The noise level and class demographics vary with teacher style but there’s nearly always a perceivable high level of energy in the classroom. When asked, these teachers talk of inquiry from the point of view of a teaching strategy for motivating students. These activities, the experts suggest, are the best teaching strategies for engaging children in the joys of learning science. The research concerning how little is learned when there is no engagement is robust. The argument for engagement is best expressed by that common chant of the 60s:

I see . . . I forget

I hear . . . I remember

I do . . . I understand

There is a danger in this view of inquiry. Unless we know more about the “doing”—*what* is being done, and *how* is it being done—we can’t assess the

truthfulness of the third assertion. This view of inquiry—commonly heard as a call for more hands-on activities in students’ school science—falls short of reform goals because not all hands-on activities are inquiry-based activities.

I’ve seen children with materials in their hands but little evidence of understanding in their minds. If you give a child a battery and a small motor with two wires, the child will connect the wires to the battery and the motor will turn. If the motor has a propeller on it, the child might make the wind blow in his or her face. Or, more often, turn it on a neighbor.

That’s a hands-on experience but a relatively weak inquiry situation. *Benchmarks for Science Literacy*, the American Association for the Advancement of Science publication agrees:

Hands-on experience is important but does not guarantee meaningfulness. (1993, p. 319)

And in the long run, I don’t believe that by itself it even engages the young mind in science.

## THE SECOND FACE GETS THE INQUIRY ACTIVITY RIGHT

At first glance, the classroom looks the same: children working with materials. But there’s a difference. The children are interacting with the materials—they’re doing an experiment.

In this image the child develops questions and devises ways to the answers *via the materials*. While the activities may have started with that important component of “messing around,” they eventually take on the purpose of the searching for answers.

In the example of the battery and motor, simply encouraging the child to ask a question—such as what will happen if the wires are reversed—and then giving the opportunity to seek answers moves the inquiry to this next level. Eventually, the questions get more complex, asking, for instance, what changes when more batteries are used. Hands-on activities when enhanced with questioning initiates a richer inquiry opportunity.

There are plenty of questions that are within the grasp of the child. The key is whether the activity allows students to engage in a dialogue with the material world. The inquiry activity involves observing, asking questions, making predictions, and thinking about the results—reflecting on the predictions—and crafting the next move.

As Wendy Saul states in her delightful introductory chapter in *Beyond the Science Kit*:

Inquiry is realized in the coming together of materials and learner.  
(Saul & Reardon, 1996. p. 7)

Good teachers recognize the ways materials and curiosity relate, and help students as they tentatively or bullishly try to connect their own questions to ways of “finding out.” Good teachers also work with children to “make sense” of what they find and construct arguments that seem convincing to others in their scientific community.

My simple definition of the process of science and thus scientific inquiry activities points to what we’re trying to get our students to do: Science is the process of talking to the material world. Scientists understand their world by figuring out how to pose questions to the phenomena at hand. In the same way, we want our students to understand their world by learning how to ask the right questions—to the phenomena, not the teacher. It’s fortuitous that research on student learning shows that this ability is also a powerful tool for learning science. My teaching goal is to place my students in situations where they can practice having the dialogue.

One of my best inquiry workshops happened by accident.

I was invited to do something on inquiry at a summer institute for middle school teachers. I decided to do a workshop on “Batteries and Bulbs.” I hadn’t done a workshop on electricity for ages, and I thought it would be fun to show teachers the richness of that topic.

I was told I would be conducting four workshops in succession for the institute’s 120 teachers. I didn’t want to carry workshop materials for 120 people on the airplane, so I put the tiny flashlight bulbs and some wire into my carry-on and shipped the heavier batteries directly to the hotel.

When I arrived at the hotel at midnight, I informed the registration clerk that there was a package waiting for me. He returned from the back room with a confused look. My workshop materials were nowhere to be found.

Between midnight and 8 AM, I became a scavenger connoisseur. By the time the first workshop began, I had found 8 batteries, 2 packets of paper towels (luckily, different brands), a roll of masking tape, a box of rubber bands, 4 bottles of different dish soaps, some string and washers, and paper coffee cups. My well-planned workshop on inquiry had just been replaced with “Today, we’re going to look at a variety of phenomena.”

The teachers divided into small teams. I suggested they play a little, come up with some initial questions, and then decide how to ask a question *directly* to the phenomena of interest.

Some teams played with the paper towels: one team looked at the strength of the two brands of towels, another team checked out absorbency, and another found a magnifying glass and examined the towel textures. A couple of teams looked at the stretching properties of rubber bands. Then they measured stretch for different weights using the washers. (They didn't have rulers, so they made their own scales by using string and making knots of units. One team named these units after one of the team members.)

One team got fascinated with the periodic motion of pendula and with a little creative mounting on a wall was able to achieve precise, repeatable trials of amplitude versus period of swing.

This was inquiry in its purest form.

### THE THIRD FACE HAS A CONTENT DIMENSION

Engaging in the process of inquiry doesn't require a specific, organized experiment. For the teachers' workshop I wanted to create an authentic experience, having them look at some piece of the material world in a systematic fashion. It didn't matter what phenomena they investigated. Having multiple options, in fact, provided a convincing demonstration of this. Any experiment can lead to interesting investigations about the material world.

With the teachers in the workshop, I enhanced the image of inquiry by talking about the structure of inquiry. Inquiry was a content to be learned. This enhanced image is a crucial part of the two major standards efforts and, frequently, overlooked.

The two major standards efforts, one conducted by the National Research Council (NRC) and the other by the American Association for the Advancement of Science (AAAS) enhanced the image of inquiry further by declaring it to be a content to be learned.

The AAAS Project 2061 publication, *Benchmarks for Scientific Literacy* states in the first chapter:

If students themselves participate in scientific investigations that progressively approximate good science, then the picture they come away with will likely be reasonably accurate.

. . . the laboratory can be designed to help students learn about the nature of scientific inquiry. (1993, p. 9)

The *National Science Education Standards* document (NRC, 1996) lists “inquiry” in its content section and defines it as follows:

Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations. Students will engage in selected aspects of inquiry as they learn the scientific way of knowing the natural world, but they also should develop the capacity to conduct complete inquiries. (p. 23)

When inquiry becomes a content to be inquired into and learned, the role of the teacher changes from just engaging students to that of stewardship over the development of knowledgeable thinkers about inquiry. But no set of experiments, if done in a vacuum, will lead to a scientifically literate graduating student. Inquiry is a content different from other content. It’s not something to be studied for a short time and then left behind. Inquiry has a meta-content character that demands its presence while all the other content is being learned.

Both the traditional basic content and the meta-content, inquiry, must be infused into the children’s experiences. We know we cannot plod from curriculum lesson to curriculum lesson (or chapter to chapter in a textbook) without an awareness of what the child is thinking or doing. It is equally important that we do not become driven by the seductive energy of kids’ curiosity and jump from interesting to interesting phenomena without any concern for the growth of shared knowledge and a coherence of learning experiences. If left to their own devices, students will merely deepen their own misconceptions.

Expanding on the simple definition of science given above, we can add that the goal of science is to find rules of Nature. It is important that as students work within an inquiry activity they keep to the point of the inquiry—to search out Nature’s mysteries. Students need to be challenged for the evidence of an opinion or inference. And they need to learn the basic core of science as outlined in the standards documents.

## REFERENCES

- American Association for the Advancement of Science. 1993.  
*Benchmarks for science literacy*. New York: Oxford University Press.
- National Research Council. 1996. *National science education standards*. Washington, DC: National Academy Press.
- Saul, W., and J. Reardon. (Eds.) 1996. *Beyond the science kit*.  
Portsmouth, NH: Heinemann Press.

# Teaching Science as Inquiry

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## INTRODUCTION

The idea of teaching science as inquiry has a rather long history in science education. There is an equally long history of confusion about what teaching science as inquiry means and, regardless of the definition, its implementation in the classroom. In short, we espouse the idea and do not carry out the practice. Publication of the *National Science Education Standards* (National Research Council, 1996) once again brought science as inquiry to the top of educational goals. The *Standards* answer definitional questions. Teaching science as inquiry, the *Standards* explain, requires imparting not only scientific information but the skills of inquiry and, more deeply, an understanding of what scientific inquiry is about.

## INQUIRY IN ACTION

A science teacher wanted to see inquiry in action so she visited three classrooms. Her considerations included the content of lessons, the teaching strategies, the student activities, and what students learned. During five days in each classroom, she made these observations.

### Classroom 1

The students engaged in an investigation initiated by significant student interest. A student asked what happened to the water in a watering can. The can was almost full on Friday and almost empty on Monday. One student proposed that Willie the pet hamster had left his cage at night and drunk the water. Encouraged by the teacher to find a way to test this idea, the students covered the water so Willie could not drink it. Over several days they observed that the water level did not drop. The teacher then challenged the students to think about other explanations. The students' questions resulted in a series of full investigations about the disappearance of water from the container. The teacher employed strategies such as asking students to consider alternative explanations, using evidence to form their explanations, and designing simple investigations to test an explanation. The science teacher never did explain evaporation and related concepts.

### Classroom 2

In a class studying evolution, the teacher distributed two similar but slightly different molds with dozens of fossil brachiopods. The students measured the lengths and widths of the two populations of brachiopods. The teacher asked whether the differences in length and width might represent evolutionary change. As the students responded, the teacher asked—How do you know? How could you support your answer? What evidence would you need? What if the fossils were in the same rock formation? Are the variations in length and width just normal variations in the species? How would difference in length or width help a brachiopod adapt better? The fossil activity provided the context for students to learn about the relationships between the potential for a species to increase its numbers, the genetic variability of offspring due to mutation and recombination of genes, the finite supply of resources required for life, and the ensuing selection by the environment for those offspring better able to survive and leave offspring. In the end, students learned about changes in the variations of characteristics in a population—biological evolution.

### Classroom 3

In this science classroom, students selected from among several books that provided extended discussions of scientific work. Readings included *The Double Helix*, *The Beak of the Finch*, *An Imagined World*, and *A Feeling for the Organism*. Over a

three-week period, each student read one of the books as homework. Then, in groups of four, all students discussed and answered the same questions—What led the scientist to the investigation? What conceptual ideas and knowledge guided the inquiry? What reasons did the scientist cite for conducting the investigation? How did technology enhance the gathering and manipulation of data? What role did mathematics have in the inquiry? Was the scientific explanation logically consistent? based in evidence? open to skeptical review? and built on knowledge from other experiments? After reading the books and completing the discussion questions, the groups prepared oral reports on the topic, “The Role of Inquiry in Science.”

After completing the classroom visits, the science teacher summarized her observations (see Table 1).

**TABLE 1. SUMMARY OF OBSERVATIONS**

	Classroom 1	Classroom 2	Classroom 3
CONTENT OF LESSONS	Changing water level in an open container	Investigation of variations in fossils	Stories of scientists and their work
TEACHING STRATEGIES	Challenge students to think about proposed explanations and use evidence to support conclusions	Provide molds of fossils and ask questions about student measurements and observations	Provide questions to focus discussions of readings
STUDENT ACTIVITIES	Design simple, but full investigations	Measure fossils and use data to answer questions	Read and discuss a book about scientific investigations
STUDENT OUTCOMES	Develop the ability to reason using logic and evidence to form an explanation	Understand some of the basic concepts of biological evolution	Understand scientific inquiry as it is demonstrated in the work of scientists

This introduction should have engaged your thinking about teaching science as inquiry. In order to further clarify your thinking, take a few minutes and respond to the questions here. Refer to the passages or summary table as often as necessary. Select the best answers and provide brief explanations for your choices.

1. Which classroom would you cite as furnishing the best example of teaching science as inquiry?
  - A. 1
  - B. 2
  - C. 3
  - D. None of the classrooms
  - E. All of the classrooms

EXPLANATION:

2. If teaching science as inquiry is primarily interpreted to mean using laboratory experiences to learn science concepts, which classroom was the best example?
  - A. 1
  - B. 2
  - C. 3
  - D. None of the classrooms
  - E. All of the classrooms

EXPLANATION:

3. If students had numerous experiences with the same teaching strategies and the same activities devised by the students as in Classroom 1, but pursued different questions, what would you predict as the results for students?
  - A. Their thinking abilities, understanding of the subject, and understanding of inquiry will be higher than students who were in the other two classes.
  - B. Their thinking abilities, understanding of the subject, and understanding of inquiry will be lower.
  - C. Their thinking abilities would be higher and their understanding of the subject and of inquiry will be lower.
  - D. Their understanding of the subject matter will be higher and their thinking abilities along with their understanding of inquiry lower.
  - E. All learning outcomes would be the same as for students in the other two classes.

EXPLANATION:

## 24 Teaching Science as Inquiry

4. Which of these generalizations about teaching science as inquiry would the observations of the three classrooms suggest to you?
- A. Overuse of one teaching strategy may constrain opportunities to learn the subject.
  - B. Differing teaching strategies and student activities may bring differing benefits and trade-offs.
  - C. The potential learning outcomes for any one sequence of lessons may be greater than for the sum of the individual lessons.
  - D. Teaching strategies may need to differ in accordance with the result sought.
  - E. All of the above.

EXPLANATION:

5. If the teacher continues observing the three classrooms for another week, what would you recommend she look for in order to formulate an answer to the question, What is teaching science as inquiry?
- A. What the students learned about scientific inquiry.
  - B. What teaching strategies the teacher used.
  - C. What science information, concepts, and principles the students learned.
  - D. What inquiry abilities the students developed.
  - E. What teachers should know and do to achieve the different learning goals of scientific inquiry.

EXPLANATION:

6. Drawing on these observations, the science teacher proposes that teaching science as inquiry may have multiple meanings. Which of these would you recommend as a next step in her investigation?
- A. Explore how others have answered the question—What is teaching science as inquiry?
  - B. See how the *National Science Education Standards* explain Science as Inquiry.
  - C. Elaborate the implications of teaching science as inquiry.
  - D. Try teaching science as inquiry in order to evaluate the approach in school science programs.
  - E. All of the above.

EXPLANATION:

As you engaged in the review of the observations in three classrooms, what idea of inquiry did you originally apply? Assuming you are now engaged in questions about teaching science as inquiry, we can proceed to a review of several historical discussions of inquiry.

## PERSPECTIVES FROM HISTORY

In the United States, science itself was not valued prior to the mid-nineteenth century. "...faith," Charles Stedman writes, "was at least as important as empirical data and in many instances it dominated the practices of science. This faith was often a complex mixture of Christian theology, idealism, and entrenched traditions" (1987).

In the late nineteenth century, several people brought science into discussions of school and college curricula. Charles W. Eliot, president of Harvard University from 1869 to 1895, articulated the need for science and laboratory approaches in the curriculum. Louis Agassiz, also at Harvard, provided an early example of teaching science as inquiry when he had students come to his lab and study specimens. He directed field trips to the countryside and seashore, encouraged students to make their own collections, and conducted instruction by correspondence with specimen collectors around the country (Stedman, 1987).

### John Dewey

In 1909, when the presence of science in the school curriculum was bringing disagreements about what science is and thus how it should be taught, John Dewey addressed the education section of the American Association for the Advancement of Science on the topic "Science as Subject-Matter and as Method" (Dewey, 1910). Dewey's general theme was that science teaching gave too much emphasis to the accumulation of information and not enough to science as a method of thinking and an attitude of mind: "Science teaching has suffered because science has been so frequently presented just as so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject-matter." (p. 124)

Notice that in these passages, Dewey refers to aims that include the abilities of inquiry, the nature of science, and an understanding of a subject.

Surely if there is any knowledge which is of most worth it is knowledge of the ways by which anything is entitled to be called knowledge instead of being mere opinion or guess work or dogma.

Such knowledge never can be learned by itself; it is not information, but a mode of intelligent practice, an habitual disposition of mind. Only by taking a hand in the making of knowledge, by transferring guess and opinion into belief authorized by inquiry, does one ever get a knowledge of the method of knowing. (p. 125)

But that the great majority of those who leave school have some idea of the kind of evidence required to substantiate given types of belief does not seem unreasonable. Nor is it absurd to expect that they should go forth with a lively interest in the ways in which knowledge is improved by a marked distaste for all conclusions reached in disharmony with the methods of scientific inquiry. (p. 127)

Near the conclusion, Dewey makes this powerful statement.

One of the only two articles that remain in my creed of life is that the future of our civilization depends upon the widening spread and deepening hold of the scientific habit of mind; and that the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit. (p. 127)

Some ninety years ago, then, John Dewey articulated as objectives of teaching science as inquiry: developing thinking and reasoning, formulating habits of mind, learning science subjects, and understanding the processes of science. Dewey's *Logic: The Theory of Inquiry*, published in 1938, presents his stages in the scientific method: induction, deduction, mathematical logic, and empiricism. This book no doubt influenced the many science textbooks that treat the scientific method as a fixed sequence as opposed to a variety of strategies whose use depends on the question being investigated and the researchers. Discussions about the role of scientific method in science classrooms and textbooks continue in the community of science educators (Klapper, 1995; Storey & Carter, 1992).

### Joseph J. Schwab

In the late 1950s and the 1960s, Joseph Schwab published articles on inquiry (or enquiry, his preferred spelling). Schwab laid the foundation for the emergence of inquiry as a prominent theme in the curriculum reform of that era (Schwab, 1958; 1960; 1966). In 1958 he grounded in science itself his argument for teaching science as inquiry: "The formal reason for a change in present methods of teaching the sciences lies in the fact that science itself has changed. A new view

concerning the nature of scientific inquiry now controls research.” According to Schwab, scientists no longer conceived science as stable truths to be verified; they were viewing it as principles for inquiry, conceptual structures revisable in response to new evidence. Schwab distinguished between “stable” and “fluid” inquiry. These terms suggest the distinction between normal and revolutionary science as made popular by Thomas Kuhn in his classic of 1970, *The Structures of Scientific Revolutions*. Stable inquiry uses current principles to “fill a...blank space in a growing body of knowledge” (1966), while fluid inquiry is the invention of conceptual structures that will revolutionize science.

Schwab observed that teachers and textbooks were presenting science in a way that was inconsistent with modern science. Schwab in 1966 found that science was being taught “...as a nearly unmitigated rhetoric of conclusions in which the current and temporary constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths.” A “rhetoric of conclusions, then, is a structure of discourse which persuades men to accept the tentative as certain, the doubtful as the undoubted, by making no mention of reasons or evidence for what it asserts, as if to say, ‘this, everyone of importance knows to be true.’” The implications of Schwab’s ideas were, for their time, profound. He suggested both that science should be presented as inquiry, and that students should undertake inquiries.

In order to achieve these changes, Schwab argued in 1960, science teachers should first look to the laboratory and use these experiences to lead rather than lag behind the classroom phase of science teaching. He urged science teachers to consider three levels of openness in their laboratories. At the primary level, the materials can pose questions and describe methods of investigation that allow students to discover relationships they do not already know. Next, the laboratory manual or textbook can pose questions, but the methods and answers are left open. And on the most sophisticated level, students confront phenomena without questions based in textbooks or laboratories. They are left to ask questions, gather evidence, and propose explanations based on their evidence.

Schwab also proposed an “enquiry into enquiry.” Here teachers provide students with readings, reports, or books about research. They engage in discussions about the problems, data, role of technology, interpretation of data, and conclusions reached by scientists. Where possible, students should read about alternative explanations, experiments, debates about assumptions, use of evidence, and other issues of scientific inquiry.

Joseph Schwab had a tremendous influence on the original design of instructional materials—the laboratories and invitations to inquiry—for the Biological Sciences Curriculum Study (BSCS). Schwab’s recommendation paid off in the late 1970s and early 1980s when educational researchers asked questions about the effectiveness of these programs. In 1984 Shymansky reported evidence supporting his conclusion that “BSCS biology is the most successful of the new high school science curricula.”

#### F. James Rutherford

In 1964 F. James Rutherford observed that while in the teaching of science we are unalterably opposed to rote memorization and all for the teaching of scientific processes, critical thinking, and the inquiry method, in practice science teaching does not represent science as inquiry. Nor is it clear what teaching science as inquiry means. At times the concept is used in a way that makes inquiry part of the science content itself. At others, authors refer to a particular technique or strategy for bringing about learning of some particular science content.

Rutherford (1964) presented the following conclusions:

1. It is possible to gain a worthwhile understanding of science as inquiry once we recognize the necessity of considering inquiry as content and operate on the premise that the concepts of science are properly understood only in the context of how they were arrived at and of what further inquiry they initiated.
2. As a corollary, it is possible to learn something of science as inquiry without having the learning process itself to follow precisely any one of the methods of inquiry used in science.
3. The laboratory can be used to provide the student experience with some aspects or components of the investigative techniques employed in a given science, but only after the content of the experiments has been carefully analyzed for its usefulness in this regard. (pp. 80-84)

In the end, Rutherford connected to teaching science as inquiry a knowledge base for doing so. Until science teachers acquire “a rather thorough grounding in the history and philosophy of the sciences they teach, this kind of understanding will elude them, in which event not much progress toward the teaching of science as inquiry can be expected.” (p. 84)

## Project Synthesis

In the late 1970s and early 1980s, the National Science Foundation supported a project that synthesized a number of national surveys, assessments, and case studies about the status of science education in the United States (Harms & Kohl, 1980; Harms & Yager, 1981). One major portion of this review centered on the role of inquiry in science teaching and was completed by Wayne Welch, Leo Klopfer, Glen Aikenhead, and James Robinson in 1981. Their analysis revealed that the science education community was using the term “inquiry” in a variety of ways, including the general categories of inquiry as content and inquiry as instructional technique, and was unclear about the term’s meaning. The evidence indicated that “although teachers made positive statements about the value of inquiry, they often felt more responsible for teaching facts, ‘things which show up on tests,’ ‘basics’ and structure and the work ethic.” Among the teachers surveyed, the main consideration was of inquiry as an instructional technique. For not teaching science as inquiry, not employing it for introducing the content, or not using experiences oriented to inquiry, teachers gave a number of reasons. Among them were problems managing the classroom, difficulty meeting state requirements, trouble obtaining supplies and equipment, dangers that some experiments might pose for students, and concerns about whether inquiry really worked. In conclusion, the authors reported:

The widespread espoused support of inquiry is more simulated than real in practice. The greatest set of barriers to the teacher support of inquiry seems to be its perceived difficulty. There is legitimate confusion over the meaning of inquiry in the classroom. There is concern over discipline. There is worry about adequately preparing children for the next level of education. There are problems associated with the teachers’ allegiance to teaching facts and to following the role models of the college professors. (p. 40)

The portion of Project Synthesis relating to biology concludes: “In short, little evidence exists that inquiry is being used” (Hurd et al., 1980). Costenson and Lawson in 1986 presented the results of their survey of a group of biology teachers. Inquiry, some teachers had claimed, takes too much time and energy. It is too slow. The reading is too difficult, and the students are insufficiently mature. Experiments may put students at risk. Inquiry makes it hard to track the progress of students, and to place material in proper sequence. It violates the habits that teachers have developed. And it is too expensive. The objections are similar to

what Welch and his colleagues had reported. Similar results would probably be obtained for other disciplines, particularly at the secondary level. They form the substantial barriers between policies, such as that set by the *Standards* in 1996, that recommend science as inquiry and the programs exemplified in BSCS materials that incorporate into teaching science as inquiry the actual practices in science classrooms. “In our opinion,” the report on biology declares,

...the previous reasons for not using inquiry are not sufficient to prevent its use. However, to implement inquiry in the classroom we see three crucial ingredients: (1) teachers must understand precisely what scientific inquiry is; (2) they must have sufficient understanding of the structure of biology itself; and (3) they must become skilled in inquiry teaching techniques. (p. 158)

The passage makes the important distinction between inquiry as content to be understood first by teachers and then by students and inquiry as technique that teachers are to use to help students learn biology.

### Project 2061

In 1985, F. James Rutherford inaugurated Project 2061, a long-term initiative of the American Association for the Advancement of Science (AAAS) to reform K-12 education. It set the stage for the *National Science Education Standards* published in 1996 by the National Research Council (NRC). In the initial years, the project outlined what all students should know and be able to do by the time they complete the twelfth grade. Project 2061 materials such as *Science for All Americans* issued in 1989, and *Benchmarks for Science Literacy* which AAAS published in 1993, have made significant statements about teaching science as inquiry. Rutherford’s observations and recommendations presaged in 1964 the place Project 2061 assigns to the nature and history of science and that which it sets for habits of mind.

The lead chapter of *Science for All Americans* outlines recommendations for the nature of science and another provides recommendations for “Historical Perspectives.” A chapter on “Habits of Mind” includes categories of values and attitudes, manipulation and observation, communication, and very importantly, skills of critical response.

In a separate chapter on “Effective Learning and Teaching,” *Science for All Americans* makes the general recommendation, “Teaching Should Be Consistent With the Nature of Scientific Inquiry,” followed by specific advice:

- ▶ Start with Questions About Nature
- ▶ Engage Students Actively
- ▶ Concentrate on the Collection and Use of Evidence
- ▶ Provide Historical Perspectives
- ▶ Insist on Clear Expression
- ▶ Use a Team Approach
- ▶ Do Not Separate Knowing From Finding Out
- ▶ Deemphasize the Memorization of Technical Vocabulary (pp. 147-149)

*Benchmarks for Science Literacy* show specific results of learning about the nature of science, gaining historical perspectives, and acquiring good habits of mind. In addition, there is an excellent research base that indicates what students know and are able to do relative to various benchmarks.

Project 2061 also set in place goals and specific benchmarks for teaching scientific inquiry as content. Included as well are recommendations for using teaching techniques associated with inquiry.

### ***NATIONAL SCIENCE EDUCATION STANDARDS: INQUIRY AS CONTENT***

The *National Science Education Standards* (NRC, 1996) present a present-day statement on teaching science as inquiry. Defining what all students should know and be able to do by grade twelve, and what kinds of learning experiences they need to achieve scientific literacy, the document reaffirms the conviction that inquiry is central to the achievement of scientific literacy.

In 1991, the National Research Council was asked by the President of the National Science Teachers Association to coordinate efforts to develop national standards for science education. Between 1991 and 1995, the NRC produced several drafts of standards, submitted those to extensive review, and set in motion a process for developing a national consensus for the standards. In December 1995, the NRC released the *National Science Education Standards*, which presents a vision of a scientifically literate populace by describing what students should know and be able to do after thirteen years of school science. In addition to Content Standards, the document contains standards for Teaching, Professional Development, Assessment, School Science Programs, and the Educational System. Angelo Collins provided in 1995 a detailed history of the science education standards, and elsewhere I have discussed the *Standards* (and *Benchmarks*) and the aim of achieving scientific literacy (Bybee, 1997).

Release of the *Standards* again brought to the forefront in the educational community the issue of teaching science as inquiry. In the *Standards*, scientific inquiry refers to several related, but different things: the ways scientists study the natural world, activities of students, strategies of teaching, and outcomes that students should learn. The *Standards* provide this summary of inquiry:

...inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and considerations of alternative explanations. (p. 23)

The *Standards* use the term “inquiry” in two ways. Inquiry is content, which means both what students should understand about scientific inquiry and the abilities they should develop from their experiences with scientific inquiry. The term also refers to teaching strategies and the processes of learning associated with activities oriented to inquiry.

Here in summary are the standards on content in science as inquiry for grades nine through twelve:

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**TABLE 2. CONTENT STANDARD FOR SCIENCE AS INQUIRY**

---

As a result of activities in grades 9-12, all students should develop

---

- ▶ Abilities necessary to do scientific inquiry.
  - ▶ Understandings about scientific inquiry.
- 

**SCIENCE AS INQUIRY: THE ABILITIES**

Table 3 presents the abilities students should attain. Note the emphasis on cognitive abilities and critical thinking. Without eliminating activities such as observing, inferring, and hypothesizing, this emphasis differentiates the *Standards* from traditional material that concentrates on processes.

**TABLE 3. SCIENCE AS INQUIRY:  
FUNDAMENTAL ABILITIES FOR GRADES 9-12**

- 
- ▶ Identify questions and concepts that guide scientific investigations.
  - ▶ Design and conduct scientific investigations.
  - ▶ Use technology and mathematics.
  - ▶ Formulate and revise scientific explanations and models using logic and evidence.
  - ▶ Recognize and analyze alternative explanations and models.
  - ▶ Communicate and defend a scientific argument
- 

**Identify questions and concepts that guide scientific investigations.**

Students should formulate a testable hypothesis and demonstrate the logical connections between the scientific concepts guiding a hypothesis and the design of an experiment. They should demonstrate appropriate procedures, a knowledge base, and conceptual understanding of scientific investigations.

**Design and conduct scientific investigations.** Designing and conducting a scientific investigation requires introduction to the major concepts in the area being investigated, proper equipment, safety precautions, assistance with methodological problems, recommendations for use of technologies, clarification of ideas that guide the inquiry, and scientific knowledge obtained from sources other than the actual investigation. The investigation may also require students clarification of the question, method, controls, and variables; student organization and display of data; student revision of methods and explanations; and a public presentation of the results with a critical response from peers. Regardless of the scientific investigation performed, students must use evidence, apply logic, and construct an argument for their proposed explanations.

**Use technology and mathematics to improve investigations and communications.** A variety of technologies, such as hand tools, measuring instruments, and calculators, should be an integral component of scientific investigations. The use of computers for the collection, analysis, and display of data is also a part of this standard. Mathematics plays an essential role in all aspects of an inquiry. For example, measurement is used for posing questions,

formulas are used for developing explanations, and charts and graphs are used for communicating results.

**Formulate and revise scientific explanations and models using logic and evidence.** Student inquiries should culminate in formulating an explanation or model. Models should be physical, conceptual, and mathematical. In the process of answering the questions, the students should engage in discussions and arguments that result in the revision of their explanations. These discussions should be based on scientific knowledge, the use of logic, and evidence from their investigation.

**Recognize and analyze alternative explanations and models.** The aspect of standard emphasizes the critical abilities of analyzing an argument by reviewing current scientific understanding, weighing the evidence, and examining the logic so as to decide which explanations and models are best.

**Communicate and defend a scientific argument.** Students in school science programs should develop the abilities associated with accurate and effective communication. These include writing and following procedures, expressing concepts, reviewing information, summarizing data, using language appropriately, developing diagrams and charts, explaining statistical analysis, speaking clearly and logically, constructing a reasoned argument, and responding appropriately to critical comments. (NRC, 1996, pp. 175-76)

## SCIENCE AS INQUIRY: THE UNDERSTANDINGS

Table 4 summarizes the fundamental understandings that students should develop as a result of their science education.

**TABLE 4. SCIENCE AS INQUIRY:  
FUNDAMENTAL CONCEPTS FOR GRADES 9-12**

- 
- ▶ Conceptual principles and knowledge guide scientific inquiries.
  - ▶ Scientists conduct investigations for a variety of reasons including discovering new aspects of the natural world, explaining recently observed phenomena, testing conclusions of prior investigations, and making predictions of current theories.

- ▶ Scientists rely on technology to enhance the gathering and manipulation of data.
  - ▶ Mathematics is essential in scientific inquiry.
  - ▶ Scientific explanations must adhere to criteria, such as logical consistency, rules of evidence open to questioning and based on historical and current knowledge.
  - ▶ Results of scientific inquiry—new knowledge and methods—emerge from different types of investigations and public communications among scientists.
- 

**Conceptual principles and knowledge guide scientific inquiries.**

Scientists usually inquire about how physical, living, or designed systems function. Historical and current scientific knowledge influence the design and interpretation of investigations and the evaluation of proposed explanations made by other scientists.

**Scientists conduct investigations for a wide variety of reasons.** For example, they may wish to discover new aspects of the natural world, explain recently observed phenomena, or test the conclusions of prior investigations or the predictions of current theories.

**Scientists rely on technology to enhance the gathering and manipulation of data.** New techniques and tools provide new evidence to guide inquiry and new methods to gather data thereby contributing to the advance of science. The accuracy and precision of the data, and therefore the quality of the exploration, depends on the technology used.

**Mathematics is essential in scientific inquiry.** Mathematical tools and models guide and improve the posing of questions, gathering of data, constructing explanations, and communicating results.

**Scientific explanations must adhere to criteria.** A proposed explanation, for instance, must be logically consistent; it must abide by the rules of evidence; it must be open to questions and possible modification; and it must be based on historical and current scientific knowledge.

**Results of scientific inquiry—new knowledge and methods—emerge from different types of investigations and public communication among scientists.** In communicating and defending the results of scientific inquiry, arguments must be logical and

demonstrate connections between natural phenomena, investigations, and the historical body of scientific knowledge. In addition, the methods and procedures that scientists have used to obtain evidence must be clearly reported to enhance opportunities for further investigation. (NRC, 1996, p. 176)

### ***NATIONAL SCIENCE EDUCATION STANDARDS:*** **INQUIRY AS TEACHING STRATEGIES**

I turn to questions that emerge from the discussion of inquiry as content. How do science teachers help students attain the abilities and understanding described in the Science as Inquiry Standards? And what do the *Standards* say about teaching?

#### **Science Teaching Standards**

The Science Teaching Standards (see Table 5) provide a comprehensive perspective for science teachers who wish to provide students with the opportunities to experience science as inquiry. The *Standards* advocate the use of diverse teaching techniques:

Although the *Standards* emphasize inquiry, this should not be interpreted as recommending a single approach to science teaching. Teachers should use different strategies to develop the knowledge, understandings, and abilities described in the content standards. Conducting hands-on science activities does not guarantee inquiry, nor is reading about science incompatible with inquiry. Attaining the understanding and abilities described in [the prior section] cannot be achieved by any single teaching strategy or learning experience. (NRC, 1996, pp. 23-24)

**TABLE 5. SCIENCE TEACHING STANDARDS**

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- A. Teachers of science plan an inquiry-based science program for their students.
- B. Teachers of science guide and facilitate learning.

- C. Teachers of science engage in ongoing assessment of their teaching and of student learning.
  - D. Teachers of science design and manage learning environments that provide students with the time, space, and resources needed for learning science.
  - E. Teachers of science develop communities of science learners that reflect the intellectual rigor of scientific inquiry and the attitudes and social values conducive to science learning.
  - F. Teachers of science actively participate in the ongoing planning and development of the school science program.
- 

### What Should Science Teachers Know, Value, and Do?

Science teachers should know the differences between inquiry as a description of methods and processes that scientists use; inquiry as a set of cognitive abilities that students might develop; and inquiry as a constellation of teaching strategies that can facilitate learning about scientific inquiry, developing the abilities of inquiry, and understanding scientific concepts and principles.

In placing this discussion of teaching after the discussion of content, I have wanted to make the point that the desired outcomes—learning science as subject and science as inquiry—present the primary answer to the question, “What is teaching science as inquiry?” The very character of science as inquiry lodges in strategies for teaching inquiry.

### A PRESENT-DAY PERSPECTIVE ON TEACHING SCIENCE AS INQUIRY

There is, in my view, a rich and thorough intellectual foundation for teaching science as inquiry. That foundation includes work by Bakker and Clark in 1988, Moore in 1993, Duschl in 1994, and in 1997 Hatton and Plouffe, and Mayr.

### Constructing a New View of Inquiry

My use of the initial observations of classrooms and questions set the context for this essay. The questions based on those observations allowed you to think deeply about the observations and explore several issues associated with the theme of teaching science as inquiry. Returning to the observations and questions now provides an opportunity to separate inquiry as content and inquiry as teaching strategies and establish a perspective on teaching science as inquiry.

Question one probes the dominant perception of teaching science as inquiry. If your view was that inquiry is primarily activity directed by students, you probably answered A. If it was using laboratory experiences to teach the subject, you probably answered B. Few teachers answer C, for most do not view understanding scientific inquiry as a primary aim of school science. Those who responded D probably explained that some elements of all three classrooms contained inquiry.

Question two emphasizes the conception that most secondary teachers hold of inquiry: inquiry as technique or laboratory experiences for learning science concepts. The best answer is B. In classroom one, students had many opportunities to develop the abilities of inquiry; and students in classroom three developed an understanding of scientific inquiry. But neither of the two classes concentrated on the subjects of science: concepts of life, earth, and physical phenomena.

Question three was designed to probe the idea of inquiry as teaching strategy and engage your thinking about this as a singular approach to teaching science and the implied learning outcomes for students. If you used this approach all the time, what would students learn and what would they not learn? I suggest that the best answer is C. The primary assumption here is that classroom experiences of inquiry alone do not guarantee understanding subjects. Teachers should make explicit connections between the experiences and the content of inquiry and subject.

Question four asks for a generalization about the connection between teaching strategies and learning outcomes. I suggest that the best response is E because each of the others has some basis in practical truth.

In question five, the teacher could look at any of the responses or could look at all. Response E best anticipates a theme of this essay: that science teachers must have some understanding of scientific inquiry and a variety of teaching strategies and abilities to help students learn science subjects and the content of inquiry.

Question six organizes the reader's thinking to other sections of this chapter. The evaluation of my success and yours lies in E and especially D.

## TOWARD A STANDARDS-BASED APPROACH TO TEACHING SCIENCE AS INQUIRY

Most discussions of teaching science as inquiry begin with the assumption that inquiry is a teaching strategy. Science teachers ask, “Should I use full or partial inquiries? Should the approach be guided by the teacher or left to the student?” A standards-based perspective views the situation differently. Such a perspective begins with the educational outcomes—What is it we want students to learn?—and then identifies the best strategies to achieve the outcome. Table 6 provides examples of this perspective. Reading from left to right, the table asks these questions: What content do I wish students to learn? Which teaching techniques provide the best opportunities to accomplish that? What assessment strategies most align with the students’ opportunities to learn and provide the best evidence of the degree to which they have done so?

**TABLE 6. EXAMPLES OF TEACHING AND ASSESSMENT THAT  
SUPPORT INQUIRY-ORIENTED OUTCOMES**

<b>Standards-Based Educational Outcomes</b> What should students learn?	<b>Teaching Strategies</b> What are the techniques that will provide opportunities for students to learn?	<b>Assessment Strategies</b> What assessments align with the educational outcomes and teaching strategies?
<b>Understanding Subject Matter</b> (e.g., Motions and Forces; Matter, Energy, and Organization in Living Systems; Energy in the Earth System)	Students engage in a series of guided or structured laboratory activities that include developing some abilities to do scientific inquiry but emphasize subject matter (e.g., laws of motion, $F=ma$ , etc.)	Students are given measures that assess their understanding of subject matter. These may include performance assessment in the form of a laboratory investigation, open-response questions, interviews, and traditional multiple choice.
<b>Developing Abilities Necessary to Do Scientific Inquiry</b> (e.g., students formulate and revise scientific explanations and models using logic and evidence)	Students engage in guided or structured laboratory activities and form an explanation based on data. They present and defend their explanations using (1) scientific knowledge and (2) logic and evidence. The teacher emphasizes some inquiry abilities in the laboratory activities used for subject-matter outcomes.	Students perform a task in which they gather data and use that data as the basis for an explanation.

**Developing Abilities Necessary to Do Scientific Inquiry** (e.g., students have opportunities to develop all the fundamental abilities of the standard)

Students complete a full inquiry that originates with their questions about the natural world and culminates with a scientific explanation based on evidence. The teacher assists, guides, and coaches students.

Students do an inquiry without direction or coaching. The assessment rubric includes the complete list of fundamental abilities.

**Developing Understandings about Scientific Inquiry** (e.g., scientific explanations must adhere to criteria such as: a proposed explanation must be logically consistent; it must abide the rules of evidence; it must be open to question and possible modification; and it must be based on historical and current scientific knowledge)

The teacher could direct students to reflect on activities from several laboratory activities. Students also could read historical case studies of scientific inquiry (e.g., Darwin, Copernicus, Galileo, Lavoisier, Einstein). Discussion groups pursue questions about logic, evidence, skepticism, modification, and communication.

Students are given a brief account of a scientific discovery and asked to describe the place of logic, evidence, criticism, and modification.

In Table 6, I provide examples that answer questions about teaching science as inquiry. In developing the examples in this table, I tried to hold to a clear understanding of the realities of standards, schools, science teachers, and students. Science teachers must teach the basics of subjects. The content standards for physical, life, and earth and space sciences provide teachers with an excellent set of fundamental understandings that could form their educational outcomes. After identifying the educational results, teachers must consider the effective teaching strategies and recognize that we have a considerable research base for the concepts that students hold about many basic concepts of science. We also have some comprehension of the processes and strategies required to bring about conceptual change (Berkheimer & Anderson, 1989; Hewson, 1984; Hewson & Hewson, 1988; Gazzetti et al., 1993; King, 1994; Lott, 1983). The teaching strategies include a series of laboratory experiences that help students to confront current concepts and reconstruct them so they align with basic scientific concepts and principles such as those in the *Standards*. For teaching science as inquiry, a variety of educators have described methods compatible with standards-based approaches to teaching science as inquiry (American Chemical Society, 1997; Bingman, 1969; Connelly et al., 1977; Layman, Ochoa, & Heikkinen, 1996; Novak, 1963; Hofstein & Walberg, 1995).

Using investigations to learn subjects provides the first opportunities for students to develop the abilities necessary to do scientific inquiry. For teaching sci-

ence concepts, a series of laboratories might encourage the use of technology and mathematics to improve investigations and communications; the formulation and revision of scientific explanations and models by use of logic and evidence; and the communication and defense of a scientific argument. But science teachers must decide for themselves the appropriate abilities and make them explicit in the course of the laboratory work.

A second educational outcome, very closely aligned with learning subjects, is developing abilities necessary to do scientific inquiry. Laboratories provide many opportunities to strengthen them. These outcomes were in the background of the discussion of subject matter; here they are in the foreground. Science teachers could indeed base the activity on content, such as motions and forces, energy in the earth's system, or the molecular basis of heredity, but they could make several of the fundamental abilities the explicit outcomes of instruction. Over time, students would have ample opportunities to develop all of them. This approach to teaching science as inquiry overlaps and complements the science teacher's effort to cultivate an understanding of science concepts. The teacher structures the series of laboratory activities and provides varying levels of direct guidance.

A further result also sharpens abilities necessary for scientific inquiry. But now students have opportunities to conduct a full inquiry, which they think of, design, complete, and report. They experience all of the fundamental abilities in a scientific inquiry appropriate to their stage of sophistication and their current understanding of science. The science teacher's role is to guide and coach. The classic example of this is the science fair project.

Finally, we come to the aspect of teaching science as inquiry that is most frequently overlooked. I refer to developing understandings about scientific inquiry. On the face of it, this seems like an educational outcome that would be easy to accomplish once the science teacher has decided to instruct by means of an activity or laboratory and has gained an understanding of inquiry. Numerous ways are available of having students identify, compare, synthesize, and reflect upon their various experiences founded in inquiry. Case studies from the history of science provide insights about the processes of scientific inquiry. Developing students' understanding of scientific inquiry is a long-term process that can be implemented with educational activities such as are mentioned here.

Questions of time, energy, reading difficulties, risks, expenses, and the burden of the subject need not be rationalizations for not teaching science as inquiry. Nurturing the abilities of inquiry is consistent with other stated goals for science teaching, for example, critical thinking; and it complements other

school subjects, among them, problem solving in mathematics and design in technology. And understanding science as inquiry is a basic component of the history and nature of science itself.

## CONCLUSION

Most evidence indicates that science teaching is not now, and never has been, in any significant way, centered in inquiry whether as content or as technique. Probably the closest the science education community came to teaching science as inquiry was during the 1960s and 1970s as we implemented the curriculum programs spurred by Sputnik and provided massive professional development experiences for teachers. The evidence does indicate that these programs were effective for the objectives related to inquiry that were emphasized in that era. Although science educators continue to chant the inquiry mantra, our science classrooms have not been transformed by the incantations.

The *Standards* have restated and provided details of what we mean by teaching science as inquiry. Appropriately viewed, inquiry as science content and inquiry as teaching strategies are two sides of a single coin. Teaching science as inquiry means providing students with diverse opportunities to develop the abilities and understandings of scientific inquiry while also learning the fundamental subjects of science. The teaching strategies that provide students those opportunities are found in varied activities, laboratory investigations, and inquiries initiated by students. Science teachers know this simple educational insight. It is now time to use the *Standards* and begin a new chapter where we act on what we know and teach science as inquiry.

## REFERENCES

- American Association for the Advancement of Science. 1993. *Benchmarks for science literacy*. New York: Oxford University Press.
- American Chemical Society. 1997. *Chemistry in the national science education standards: A reader and resource manual for high school teachers*. Washington, DC: American Chemical Society.
- Bakker, G., and C. Clark. 1988. *Explanation: An introduction to the philosophy of science*. Mountain View, CA: Mayfield.

- Berkheimer, G., and C.W. Anderson. 1989. The matter and molecules project: Curriculum development based on conceptual change research. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, San Francisco.
- Bingman, R.M. (Ed.) 1969. *Inquiry objectives in the teaching of biology*, position paper, Vol. 1, No. 1. Kansas City, MO: Mid-continent Regional Educational Laboratory and Biological Sciences Curriculum Study.
- Bybee, R.W. 1997. *Achieving scientific literacy: From purposes to practice*. Portsmouth, NH: Heinemann Press.
- Collins, A. 1995. National science education standards in the United States: A process and a product. *Studies in Science Education* 26:7-37.
- Connelly, F. M., M. Finegold, J. Clipsham, and M.W. Wahlstrom. 1977. *Scientific enquiry and the teaching of science*. Toronto, Ontario: The Ontario Institute for Studies in Education.
- Costenson, K., and A. Lawson. 1986. Why isn't inquiry used in more classrooms? *The American Biology Teacher* 48 (3):150-158.
- Dewey, J. 1910. Science as subject matter and as method. *Science* 121-127.
- Dewey, J. 1938. *Logic: The theory of inquiry*. New York: MacMillan.
- Duschl, 1994. Research on the history and philosophy of science. In *Handbook of research on science teaching and learning* edited by D. H. Gabel, 443-465. New York: Macmillan.
- Gazzetti, B. J., T.E. Snyder, G.V. Glass, and W.S. Gamas. 1993. Promoting conceptual change in science: A comparative meta analysis of instructional interventions from reading education and science education. *Reading Research Quarterly* 28(2):117-158.

- Harms, N., and S. Kohl. 1980. *Project synthesis*. Final report submitted to the National Science Foundation. Boulder, CO: University of Colorado.
- Harms, N. C., and R.E. Yager. (Eds.) 1981. *What research says to the science teacher*. Vol. 3. Washington, DC: National Science Teachers Association.
- Hatton, J., and P. B. Plouffe. 1997. *Science and its ways of knowing*. Upper Saddle River, NJ: Prentice-Hall.
- Hewson, M. G. A. 1984. The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science* 13:1-13.
- Hewson, P., and M.G.A. Hewson. 1988. An appropriate conception of teaching science: A view from studies of learning. *Science Education* 72(5):597-614.
- Hofstein, A., and H.J. Walberg. 1995. Instructional strategies. In *Improving science education*, edited by B.J. Fraser and H.J. Walberg. Chicago: University of Chicago Press.
- Hurd, P. D., R.W. Bybee, J.B. Kahle, and R. Yager 1980. Biology education in secondary schools of the United States. *The American Biology Teacher* 42(7): 388-410.
- King, A. 1994. Guiding knowledge construction in the classroom: Effects of teaching children how to question and how to explain. *American Educational Research Journal* 31(2): 338-368.
- Klapper, M. H. 1995. Beyond the scientific method. *The Science Teacher* 36-40.
- Kuhn, T. S. 1970. *The structure of scientific revolutions*, rev. ed. Chicago: University of Chicago Press.

- Layman, J. W., G. Ochoa, and H. Heikkinen. 1996. *Inquiry and learning: Realizing science standards in the classroom*. New York: College Entrance Examination Board.
- Lott, G. W. 1983. The effect of inquiry teaching and advanced organizers upon student outcomes in science education. *Journal of Research in Science Teaching* 20(5): 434-438.
- Mayr, E. 1997. *This is biology: The science of the living world*. Cambridge, MA: The Belknap Press of Harvard University Press.
- Moore, J. A. 1993. *Science as a way of knowing: The foundations of modern biology*. Cambridge, MA: Harvard University Press.
- National Research Council. 1996. *National science education standards*. Washington, DC: National Academy Press.
- Novak, A. 1963. Scientific inquiry in the laboratory. *The American Biology Teacher* 342-346.
- Rutherford, F. J. 1964. The role of inquiry in science teaching. *Journal of Research in Science Teaching* 2:80-84.
- Rutherford, F.J., and A. Ahlgren. 1989. *Science for all Americans*. New York: Oxford University Press.
- Schwab, J. J. 1958. The teaching of science as inquiry. *Bulletin of the Atomic Scientists* 14:374-379.
- Schwab, J. J. 1960. Enquiry, the science teacher, and the educator. *The Science Teacher* 6-11.
- Schwab, J. 1966. *The teaching of science*. Cambridge, MA: Harvard University Press.
- Shymansky, J. A. 1984. BSCS programs: Just how effective were they? *The American Biology Teacher* 46(1):54-57.

Stedman, C. H. 1987. Fortuitous strategies on inquiry in the good ole days. *Science Education* 71(5): 657-665.

Storey, R. D., and J. Carter. 1992. Why the scientific method?  
*The Science Teacher* 18-21.

Welch, W. W., L.E. Klopfer, G.S. Aikenhead, and J.T. Robinson. 1981.  
The role of inquiry in science education: Analysis and recommendations. *Science Education* 65(1): 33-50.

# Considering the Scientific Method of Inquiry

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## OVERVIEW

The purpose of this book is to encourage the teaching of scientific inquiry. In order to do so properly, we need to understand the nature of scientific inquiry and to reconsider some of the most common conceptions associated with what the phrase “scientific inquiry” means. To do otherwise is to run the risk of teaching ideas that are incorrect or misleading in the light of what is currently known. This chapter provides a number of considerations toward teaching a rich, interesting, and reasonably current view of scientific inquiry.

In many instances in science education, scientific inquiry is equated or nearly equated with the traditional notion of the scientific method. Yet much of the work in the history and philosophy of science has provided serious, well-grounded criticisms of the traditional scientific method. Many, if not most, philosophers and historians of science would argue that there is no singular scientific method that properly describes either how science does work or how it should. Others would go so far as to argue that there is virtually no meaning to the phrase “scientific method.”

Because the traditional version of the method is still taught and modeled in science and science education courses while remaining dominant within science

curricula at all levels, and, perhaps most importantly in the thinking of the general public, simply attacking the use of the traditional scientific method would almost certainly fail to provide much assistance to present teachers of science. The traditional idea of the scientific method is just too deeply entrenched in our culture to be replaced quickly or easily. For that reason, the approach that we have taken is to examine the conventional method in the light of developments in the history and philosophy of science and to suggest ideas for improving its use. This scheme cannot take full account of recent criticisms that challenge the very core of the traditional idea of a scientific method, but it offers some improvements in the conception of the method that we present to our students.

### WHAT IS TAUGHT?

All science teachers try to present an accurate and coherent view of the science discipline they are teaching. In each case, we have our own particular idea of scientific inquiry, usually that which we were taught early through texts, lectures, textbook problems, and laboratory or field exercises. The most common view we learned is the traditional scientific method, a generalized, single sequence of several steps for solving problems.

The method is often introduced with paragraphs such as these:

Much of the work done in biology is to solve problems. Problems are not solved by flipping a coin or taking a guess as to the outcome. Scientists use a series of steps called the scientific method to solve problems.

Have you ever tried to turn on a light and found that it didn't work? Maybe you have turned the key in a car's ignition and the car didn't start. If you have had problems like those, you probably have used the scientific method.

The method itself goes something like this, taken nearly verbatim, as were the preceding passages, from high school biology textbooks.

1. Recognize and research the problem.
2. Form a hypothesis—a statement that can be tested.
3. Conduct an experiment in which you control variables to test the hypothesis.
4. Collect, organize, and analyze all relevant data.
5. Form your conclusions—which may lead to another hypothesis.

6. Present the theory... a hypothesis that has been tested again and again by many scientists with similar results each time.

The above method includes the ideas that science is objective and that conclusions are justified by formal logic and unbiased observations. The claim then emerges that the knowledge generated by the method is the truth about the natural world.

The method is usually presented in expository text and lectures explaining the steps. The presentation is occasionally reinforced by historical vignettes, such as a discussion of Torricelli's experimentation with the mercury barometer and Pasteur's experiments with generation. The method, either in whole or in parts, is also taught through the use of laboratory activities and formalized laboratory reports addressing mealworm behavior, perhaps, or the conditions necessary for plant growth, the conservation of matter, the behavior of gases or classification of various organisms. Typical activities would be collecting plants, insects, and rocks, measuring temperature, pressure, pH, current, mineral hardness, and barometric pressure, or classification of rocks and minerals, plants and animals, and elements. Finally, there is occasionally a disclaimer indicating that the steps might not always be used in this order or that some other way might be involved. The most commonly cited other way is probably "by accident" such as in the case of Roentgen's discovery of x-rays or in reverie such as when Kekule purportedly discovered the structure of benzene while gazing into a fire and seeing images of snakes forming rings by chasing their tails.

## WHY TEACH THE TRADITIONAL VIEW OF SCIENTIFIC INQUIRY?

### The Successes of the Scientific Method

The most obvious reason for continuing this view of the scientific method is that the method has a long history of achievement within Western culture. It was a successful competitor to the belief that all knowledge was revealed by God through chosen messengers. As Galileo and others found out, the idea that an individual could come to know the world through the use of the senses and reasoning was not popular with the church and governments of the age. Yet this way of thinking about ourselves led to intellectual, spiritual, political, and economic freedom. Not only new ways of coming to understand the natural world but new forms of viewing human nature, new systems of government, and new economic systems emerged. The development of the scientific method was one of the greatest intellectual revolutions in the history of the world.

The scientific method was also perceived as resulting in scientific laws and theories that made order out of chaos, rendered nature predictable, and promised individuals that they could utilize, manage, and control the environment for human benefit. The results of the use of the scientific method were seen to be the essential precursor to technological advances of the industrial revolution and with it the leisure time, the amenities, the economic security, and the military defenses of modern democracies. We greatly altered and improved our lives in many ways by using our belief in the scientific method.

The presentation of the scientific method provided a framework, some would say paradigm, for extraordinarily productive research programs. This was true for the sciences, and the philosophy of science as well. Within the sciences, innumerable inquiries relied on the belief that the observations and the logic of the method provide true results.

In the philosophy of science, the scientific method became the object of research itself. Investigators studied how this method improves the confidence of scientists in their claims about the natural world. More specifically studied was the logic of the scientific method—how it was that the method could be said to provide knowledge that was proven to be true or false. Along the way, the ways in which the method is fallible were also defined: when it would not resolve the question of whether a knowledge claim was logically true.

Complementary studies of the relationships between conceptual knowledge and the method, especially in the last half of the twentieth century, elaborated the understanding of how much of modern belief about the world depended on the traditional scientific method. Researchers studied whether observations are unbiased reflections of sensory impressions, whether the method could generate new and trustworthy laws and concepts, how the public and private lives of scientists influence their research, how the culture of a particular time does so, how intricately technology and the sciences are intertwined, and how many other factors influence modern beliefs about the natural world. All of this research was possible and necessary because the traditional scientific method was highly regarded in the sciences and many other areas of western culture, and because its relentless practice of skeptical examination and reexamination could even turn to questioning the method itself.

Because the development of the scientific method was directly and positively related to developing intellectual freedom, new forms of government, technological development, and economic and social history, the method became deeply engrained in modern culture. The scientific method therefore became a part of what we taught to our students.

## The Scientific Method and “Best Thinking”

The public and educators came to perceive the scientific method as a highly valuable way of thinking in many (if not all) of the circumstances of daily life. John Dewey in 1916 and a host of others argued that the scientific method was the pinnacle of human thought. At the very least, educators have argued that the critical thinking skills that make up the scientific method are important in themselves.

There is evidence that faith in the traditional scientific method goes back at least as far as the late 1600s in children’s didactic literature, in the writings of Locke and Rousseau as they became popularized at the end of the 1700s, and in the rationales late in the nineteenth century for developing mental capacities by the exercise of disciplined scientific thought. The nature study movement, the Progressive Education movement, curriculum development and teacher education programs of the National Science Foundation, and the more recent *Benchmarks for Science Literacy* of 1993 and *National Science Education Standards* of 1996 have insisted on the necessity for mastering the method.

Our profession has always sought something we could teach that would make problem solving easier and critical thinking more precise. We thus have been seeking a magical intellectual prescription—a way of thinking that is learnable in a finite time with limited resources, and applicable to multiple areas of our life. We have good social, political, and economic reasons to believe that the scientific method can be that prescription and there has been extensive additional support from various philosophical and psychological theories. The method appears to be simple to understand and simple to teach. There are a few steps to learn, they can be used over and over again, and each step in its own right seems to be achievable by students at various ages and levels of knowledge and skill.

## The Scientific Method, Psychology, and Science Education

The status and promise of the scientific method guaranteed that it would be part of what is taught in science classes. But there is another reason. The traditional method was also closely related to the psychologies that have declared what our students should learn and how they should be taught.

The behaviorism that J. B. Watson proposed in 1924, E. L. Thorndyke in 1932, and B. F. Skinner in 1971 dominated the profession’s view of human learning from the early 1900s up through the early 1970s. Behaviorism was predicated on a number of ideas that were consistent with the traditional view of the scientific method. It embodied deep commitment to empiricism. In

behaviorism, this translates into the idea that people need only to depend upon direct observations of overt behavior in association with direct observations of environmental stimuli: that to understand learning, we only need to examine stimuli, responses, and patterns of explicit rewards. The behaviorists were deeply committed as well to formal, logical experimentation for testing hypotheses. To establish laws of learning, they used their own experimentation (often using animals as substitutes for human beings). Thorndyke's law of effect, which locates motivation in the arousal and satisfaction of primitive needs and desires, is one of the most prominent examples. Behaviorists, in sum, strove to be objective and scientific by emulating their colleagues in the natural sciences.

Since both the psychology of learning and the philosophy of science during the first sixty or seventy years of the century shared the most central beliefs about how people have come to learn about the natural and human world, it was inevitable that science education would become committed to the scientific method and behaviorism alike. After the Second World War, many educators utilized behaviorist theories to help define what students should learn—by stating behavioral objectives; how the objectives should be sequenced—in learning hierarchies; the conditions under which the students would learn—according to the laws of rewards in behavior modification; and how they should be tested—objectively and strictly by reference to the behaviors stated in the objectives. Even in the face of significant challenges from cognitive psychology beginning in the late 1960s, behaviorism has remained prominent (yet sometimes camouflaged) in many of our ways of thinking about science curriculum, instruction, and assessment.

## NEW CONSIDERATIONS OF THE SCIENTIFIC METHOD

The most recent analyses of the scientific method, however, as well as various aspects of the studies that have occurred since the publication of Bacon's *Novum Organum* in 1620, have provided significant challenges to the traditional formulation. Understanding what has been learned in recent years about the scientific method provides a much richer and deeper understanding of the traditional scientific method. This more complete understanding is what our students need to learn.

## Objectivity of the Scientific Method

The scientific method was originally and continues to be put forward as unbiased by prejudices and preconceptions, dependent only on the observations from nature. These observations were thought to be directly related to unambiguous sensory impressions—what people see, hear, taste, smell, and feel. The method was considered to be free of any particular theory, and in fact was expected to generate correct theory. The idea that theory follows from the method and is uninfluenced by anything other than the observations (and logic) is no longer defensible from either a philosophical or a psychological perspective. It's now known that at any level beyond the fundamental physiological responses, people always have preconceptions that filter what they sense: that is, their observations.

This is the case at even the basic level. Different people viewing the same sheet of colored paper may report quite different observations. One sees blue, another green, and another aquamarine. While this difference in observation may seem trivial, in the classification of various natural objects it can become quite important. In the identification of rock types in thin section under a microscope, one person sees beautifully colored crystalline patterns; another sees a specific type of igneous rock. A geologist traveling across the landscape is likely to see layered sedimentary beds that she interprets as a simple onlap-offlap sequence resulting from successive transgressions and regressions of continental seas. Her traveling companion may see nothing but rocks in layers. But being a biologist, he may catch dramatic differences between flora and fauna in ravines and those on the plateau and interpret those as the result of differences in local climatic and soil conditions between the two locations. Both people literally see the world by means of what they already know and believe about the natural world.

Preconceptions or a theory of what is in the world, how it works, how it looks, feels, smells, tastes, and sounds, is a major determinant of what people observe and how they interpret those observations. These theories are in large part socially constructed from formal schooling—plate tectonics, Darwinian evolution, kinetic molecular theory; from the cultural and linguistic notions of a particular society—“Close the door: You're letting the heat out and the cold in”; from what features of a phenomenon the interpreter has or has not encountered directly—you see moving objects slowing down, not traveling on and on forever in a straight line until some force acts on them as physicists say they do, and you do not regularly observe and notice the conservation of mass.

In each step of the traditional scientific method, prior knowledge and belief condition observations, and this directly confronts the very foundation of that

traditional view. As F. Suppe summarized in 1977 the research of Russell Norwood Hanson, “one’s scientific view of the world is theory laden, viewed through a conceptual pattern. Part of this view is a function of the meaning one attaches to terms within a context; part of it is a function of the law-like generalizations, hypotheses, and methodological presuppositions that one holds in context.” (p.163)

Recommendation. Students should be taught that whatever aspect of the scientific method is being considered, it is influenced by their initial conceptions or theories of the natural world—what is there, how it works, how it can be observed, and how results can be interpreted. In addition, they should learn that their observations are dependent on the ideas they use while making them, that observations alone are not infallible determinants of the validity of a scientific law, and that the ideas we ask them to learn are essential to their being able to understand the natural world on their own.

### Recognize and Research the Problem

Recognizing a problem must begin with an understanding of what defines something as problematic. L. Laudén in 1977 identified two major types of problems, empirical and conceptual. When problems are proposed in science classrooms, they are almost always empirical. Conceptual problems are rarely if ever considered.

What is commonly referred to as an empirical problem exists when someone expects a certain observation such as particular yield from a chemical experiment and obtains something else. The anomalous difference between what initial theory predicts and what is observed constitutes the problem. People expect to see that a deck of cards contains red diamonds and red hearts and black spades and black clubs. Only in relation to this standard expectation do they see a red spade or a black diamond as a problem. If they expected that the colors would be red spades and black diamonds, they would see no problem at all. The history of science is replete with examples that fit this form. Roentgen’s discovery of x-rays occurred because he recognized that a barium platinocyanide screen glowed while he was working with cathode rays when he thought it should not have done so. Lavoisier’s discovery of oxygen as a distinct species was possible only because he expected that the phlogiston theory was flawed and was thus predisposed to see anomalies in his experiments (Kuhn, 1970).

A conceptual problem has to do with the inadequacy of a theory on grounds other than its inability to account for observations. Among the differing sorts of

conceptual problems is the discovery that a theory is self-contradictory. Theories can also fail to provide clearly the explanation that they seem to promise. Faraday's early model of electrical interaction did not eliminate the notion of actions at a distance as promised. Theories can be shown to be circular. Among them was the early kinetic molecular theory that postulated that gases are elastic because molecules are elastic.

Perhaps more important are conceptual problems that occur when one theory conflicts with another while both account for the relevant observations. In some cases, accepting one theory means the other cannot be accepted. Ptolemy's astronomy solved the problems of retrograde motion that had plagued the Greek astronomers but violated the idea that the motion of planets is perfect, that is, circular about the earth at a constant speed. In other cases, the problem is that two theories seem to account for a particular phenomenon nearly equally well. The behavior of light has been seen as explainable by references to either particles or waves. Other conflicts between theories occur when one makes the other unlikely (implausibility) or one seems to have offered no support or contradiction for another when it seems that being about the same class of phenomena they should be related.

Recommendation. Students should be taught that what counts as a scientific problem depends upon what theories or initial ideas about the natural world are being used; and that there are two primary types of scientific problems—empirical and theoretical. The study of both types of problems and their resolution needs to be a significant part of the science curriculum.

### Form a Hypothesis — A Statement That Can be Tested

A primary consideration regarding the formulation and testing of hypotheses is that not all scientific problems can be resolved by observational testing of a hypothesis. Some scientific problems are conceptual in nature. These must be solved by the creation of new ideas. Every scientific field of study has examples of problems that were solved by a new idea and not by observations alone. Copernicus' placing the sun at the center of the universe in place of the earth is one of the most widely known. Wegner's theory of continental drift is another.

It is also necessary to remember that hypotheses are the result of the researcher's theory of the phenomena and are restrained by it. Scientists and people in general have some more or less well-formulated set of beliefs about the phenomena they encounter. Without them, thought would be impossible. The formulation of a hypothesis that actually will improve an understanding of

the phenomena under study is a highly creative intellectual act. That creation is based on the quality of the researchers' initial theory, their knowledge of the methods available for testing the hypothesis, and their theory of what observations will be relevant. The formulation of the hypothesis about how some natural phenomenon works—that is, predicting what will happen if—is a major part of the fun and excitement of scientific inquiry, but the inquirer must be conceptually prepared to do so.

Recommendation. Students should learn that scientific problems can be solved by observations and by the creation of new theories.

### Conduct an Experiment That Will Test the Hypothesis

Some scientists, philosophers of science, and science educators have developed the idea that the experiment, if not the one and only way of learning the truth about the natural world, is at least the primary and most certain way. E. Mayr proposed in 1997 that this outdated perception probably results from the “rigorous experiment” that was the primary tool of the physics of mechanics during the early part of the scientific revolution. However this has come about, it is absurd and contradicted by the methods that are in use in many fields of study.

Collecting and cataloging the natural objects and processes of the world have been considered scientific study for millennia. Biologists, geologists, astronomers, and chemists have been concerned with the question of what objects are there in this world and universe, their relationships to one another in time and space, and how humankind could organize its thinking about them. It is not too far from the truth to say that all sciences are founded on collecting and classifying. The collecting, moreover, has gone on in a myriad of ways that are not experimental. People have watched the sky using everything from the naked eye to arrays of radio telescopes. Geologists have mapped the earth beginning with little more than their legs, compasses, and notebooks and now use seismographs, satellite imagery, sonar, and radar. Modern chemistry was preceded by many years of alchemy during which a great deal was learned about the substances that made up the matter of the earth, air, and water. The description of phenomena has been the cornerstone of all sciences and therefore cannot be excluded from it.

In many circumstances, experimentation is impossible. Geologists do not formulate experiments as to the effects different earthquake intensities have on various geological features. The people living in the areas affected would object. Astronomers do not control and manage extraterrestrial events.

Ecologists seldom systematically poison ecosystems or remove keystone species such as the alligators in the Florida Everglades from an area to improve their ability to make predictions. In some cases, the development of physical and mathematical models and their testing are substituted. In others such as in much of astronomy, geology, paleoecology, paleontology, and climatology, studying the records of the past is the basis of predictions about the future. None of the techniques used in these inquiries are direct experimental tests, but they are certainly legitimate and essential ways of conducting scientific inquiry.

Presenting the experiment as the primary feature of scientific inquiry would surprise many great scientists in history. Most of the greatest scientific accomplishments have not been the “discovery” of some new idea by experimentation. The theories have not been discovered in the real world, but have been created by the human mind as ways of considering, observing, and accounting for experiences there. If experiments were at the core of science, then Copernicus, Lyell, and Darwin could not be called scientists.

A truly controlled experiment would have to accomplish the insurmountable task of determining all of the variables that may influence the results. What investigators actually do is to control for the variables that they have other reasons to believe do make a difference. Innumerable possible variables are unknown. Roentgen’s discovery of x-rays is a good example. The discovery of x-rays was widely attacked because many, many experiments with cathode-ray tubes had to be reconsidered so as to account for the possible effect of this previously unknown energy source.

Nor are empirical problems always resolved by experimentation. Changes in theory can render them irrelevant. The Michaelson-Morley experiments were planned to determine the drag coefficients of bodies moving through an electromagnetic aether. At the advent of special relativity theory, all questions about the elasticity, density, and velocity disappeared.

Recommendation. Students should learn that there are more methods of inquiry than experimentation, each with its own demands for rigor and justification of the claims that are made about the results; limitations are substantial on what experiments can be conducted; and limits exist on the extent to which experimentation alone can solve scientific problems.

### Collect, Organize, and Analyze All Relevant Data

Theories provide the ideas that determine what observations should be made. A high energy physicist dropped in the middle of a human genome project and asked to collect the relevant observations would probably be clueless as to what observations were even possible, let alone which ones would be relevant to the problem of unraveling the human genome. The physicist would be theoretically unprepared to participate. Even inquiry into relatively simple phenomena such as the thermal expansion of metal tubing depends on existing theory to tell what to observe. What is to be observed: the atmospheric pressure in the room, the time of day and year, the effects of noise in the laboratory, the length of the tube, the type of metal, the wall thickness, the original temperature of the tube, the type of heat source, the temperature of the heat source, where the heat source is applied to the tube, or how long the heat source is applied? Without the use of existing theories and the “laws” they encompass, then it might be necessary to consider each of these variables. If the theory is very fully developed, then only a few of these variables enter into the investigation.

Just as it is impossible to know whether all relevant variables have been controlled, it is logically impossible to tell whether all the necessary observations have been made. The observations that investigators chose to make are determined by their theory of what is relevant to the problem and no theory is or can be so complete that it tells all of what should be observed. Many times in the history of science, researchers have missed an observation when their theory did not cue them to its importance to understanding the phenomenon.

Implicit in the phrase “collect the data,” moreover are a whole set of assumptions based in theory about what methods of data collection should be used and under what circumstances. Measuring temperature is a good example. It is kinetic molecular theory that provides an understanding of what has been observed indirectly—the average kinetic energy of the molecules in the system. Guidelines driven by theory define the precision required of the instrument chosen. In some cases the temperature must be knowable to a very small fraction of a degree and in other cases anything within a few hundred degrees will suffice. The same is true with respect to visual observations. Sometimes a glance at an object will be adequate for observing what is required. At other times the need is for a hand lens, an optical microscope or an electron microscope. The decision of which observational instrument to choose is dependent on what the initial theory declares to be required.

Organizing and analyzing data cannot be done in an absolutely objective way: in a way that is unbiased by previously held ideas. A student of igneous rocks who thinks grain size and the proportions of light and dark minerals are important may choose to classify the sample according to these characteristics. But a belief that mineralogical relationships may reveal what is sought will make for a different classification and conclusions. The researcher may even use the proportions of various elements and compounds. In plant and animal taxonomy, theory may determine whether comparisons should be morphological or by the genetic materials of organisms.

Similar arguments can be made with respect to the method of organizing the data that are collected. Simple tabulations, sketches, and drawings organized into sequences, maps, the construction of physical or mathematical models, and statistical testing are all possible types of data analysis. The proper methods of analysis are determined by the theory in use.

Recommendation. Students should learn that the decisions about what data to collect, how the data are to be collected, how much data are collected, and how they are analyzed and interpreted are all dependent on theory.

### Form Your Conclusions—Which May Lead to Another Hypothesis

A component of the traditional concept of the scientific method is that deductive logic should prove or falsify a hypothesis. Philosophical studies have thrown doubt on this idea. The application of formal deductive logic cannot be used to “prove” a statement. This is well known but still presented to students. No matter how many confirming instances of a hypothesis are found, the possibility that the next instance will be disconfirming cannot be eliminated. Given the hypothesis that all ravens are black, there is no logical guarantee that the next raven will not be snow white. The law that all ravens are black therefore cannot be proven. Neither can a particular hypothesis be disproved. The difficulty is not in the relationship between evidence and the hypothesis. In truly axiomatic systems like mathematics and symbolic logic an outcome that is contrary to the one that is predicted disproves the hypothesis. The problem is that it is impossible to isolate a single hypothesis. Any hypothesis is intertwined with a complex of assumptions and ideas that constitute a theory. All that contradictory evidence can show is that there is something wrong someplace in the theoretical system in which the hypothesis is embedded. In a geologic study involving the use of x-ray diffraction a number of years ago, the results of the x-ray diffraction measurements were consistently and repeatedly contrary to what had been expected. After many days and nights of

work that included examining alternative theoretical perspectives and new explanations, expected results were found but only in the early morning hours. The problem was in the x-ray diffraction equipment, which was responding to power surges generated by daytime demands. The evidence actually contradicted an assumption about the equipment and not the hypothesis under test. The expected data were evident only when most people were asleep and the demands on the electrical system were limited.

How to conduct scientific inquiry in a way that guarantees truth is not clear. Limitations on human perception and thought and ambiguities in data and instrumentation keep the process from being entirely logical. That does not mean that it is irrational. The decisions that are made in formulating conclusions are a matter of professional judgment in the light of all of what the researcher and the researcher's associated community of scholars know. The judgment is rational in being supported by complexes of reasons, some of them empirical and logical, others theoretical. Some are even determined by the culture in which the conclusions are drawn.

Recommendation. Students should learn that scientific truth is not absolute, but represents the best of collective thinking about natural phenomena when a full range of reasons are employed for understanding them—existing theories, competing theories, logic with all its limitations, past observations, new observations, and complexes of beliefs that too often are incorrectly considered as beyond the domain of science.

### Present the Theory—A Hypothesis That Has Been Tested Again and Again by Many Scientists with Similar Results Each Time

This is perhaps one of the most misunderstood aspects of the scientific method. This last step of the method is presented as if everyone will somehow automatically accept the new theory just because a scientist or group of scientists claim to have followed the scientific method. Nothing could be further from the reality of scientific inquiry. It takes less than a few moments of reading any research journal or any newspaper to see challenges to new scientific ideas that range from gentle criticism to vicious personal attacks.

The history of science is replete with such confrontations. Scientists are challenged by claims to alternative theories, contradictory data, better methods, better analyses, and better reasoning. The scientists are challenged by assertions that the data are irrelevant and the methods invalid or poorly used. There are criticisms based on religious, social, political, and economic beliefs as well

as criticisms of the researcher's scientific status, gender, morals, ethics, academic background, innate intelligence, and probably parentage. Charges of fraud and the theft of data, methods, and ideas abound. Many of the challenges are made as a way of investigating the validity of new ideas. Many are made to protect the competing ideas in which many practicing scientists have invested their lives, fortunes, and futures. Others are related to deeply personal animosities. In any case, few if any scientific theories are accepted simply because "a hypothesis...has been tested again and again by many scientists with similar results each time."

Recommendation. Students should learn that the presentation of a new idea is not the last step. In fact, it is usually the beginning of a long and often arduous sequence of discussions, arguments, replications, new investigations, and modifications of the new idea. This whole complex of events is demanded by the scientists' scientific community and often by many others from the larger society as well. Politicians, religious figures, special interest groups, the media, and the general public often become engaged. Observations, logic, proper methodology, and experimental replications may not in themselves put an end to a question.

### A Last Consideration

Almost enough has been said about what is now known about the traditional scientific method. There is, however, one consideration that has not have been emphasized enough. Real people, with all their scientific knowledge, attitudes and biases, social and personal relationships, political, religious, and social beliefs, values, morals, and ethics, and limitations, conduct scientific inquiries. And because science is a human endeavor, no aspect of the scientific method is or can be made immune to being human. So whatever version or features of the scientific method are taught must account for the people in this fascinating, unique, powerful, and engaging enterprise. Our students need to meet the people who have investigated the natural world, learn about their theories, the associated problems, methods, observations, arguments, influences, and reasons for the claims they made about the natural world. It is at least as important that students learn something of the times and circumstances in which the inquiries were done. With this as background and consideration of how the social and cultural context influences every aspect of science, perhaps students will see and in some sense experience the excitement and satisfaction of following a curiosity about the natural world. There is a myriad of personal, social, and cultural factors that are ALWAYS critical.

## REFERENCES

- American Association for the Advancement of Science. 1993.  
*Benchmarks for science literacy*. New York: Oxford University Press.
- Dewey, J. 1916. Method in science teaching. *General Science Quarterly* 1:3-9.
- Kuhn, T. S. 1970. *The structure of scientific revolutions*. Chicago: University of Chicago Press.
- Lauden, L. 1977. *Progress and problems: Towards a theory of scientific growth*. Berkeley, CA: University of California Press.
- Mayr, E. 1997. *This is biology: The science of the living world*. Cambridge, MA: Harvard University Press.
- National Research Council. 1996. *National science education standards*. Washington, DC: National Academy Press.
- Skinner, B. F. 1971. *Beyond freedom and dignity*. New York: Alfred A. Knopf.
- Suppe, F. 1977. *The structure of scientific theories*. Urbana, IL: University of Illinois Press.
- Thorndyke, E. L. 1932. *The fundamentals of learning*. New York: Teachers College Press .
- Watson, J. B. 1924. *Behaviorism*. New York: Norton.