Some Thoughts of a Scientist On Inquiry

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What 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.

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 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."
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> 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.)
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> He said, "For example, look: the bird pecks at its feathers all the time. See it walking around, pecking at its feathers?"
> "Yeah."

> 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."
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> "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."
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> 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."
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> 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.