

Laboratories in Science Education: Understanding the History and Nature of Science

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Background

In 1997, fifteen undergraduates associated with our new interdisciplinary Biology and Society Program joined me in studying science education. I had been asked to serve as Science Advisor for our Congressman Matt Salmon through the 105th Congress, and agreed to do so only if I could develop student programs related to that assignment. Our group of science students with broad social science and humanistic interests spent an intensive two weeks preparing, reading the roughly two foot deep pile of everything we could get our hands on relating to science education and its goals. Focusing on questions about scientific literacy, we asked: what is it, why do we want it, and how do we get it?

Then we went to Washington for a week. The first morning, we met at the National Academies building, and the designated staff members started to give us a spiel with the requisite presentation on packaged overheads about the NRC *Science Education Standards* Report. They assumed, probably reasonably, a low level of preparation and had planned for a half hour to hour long meeting, which must have been what most groups would have wanted. One of my students, Brent Maddin (now a nationally certified Master Teacher in the Teach for America Program), said politely “thank you, but we have read the report. What we really want to know is why you thought you needed to do the project all over when the AAAS already had Project 2061. Why didn’t you all just work

together?” After a few minutes of surprised response, the staff called for reinforcements and we continued with a lively discussion for the next hours that carried us through lunch time. We all learned a lot about making assumptions.

One clear assumption as we marched around Washington, to NSF, the AAAS, OSTP, the Department of Education, Congress, and assorted other groups was that science education was broken. We still hear that refrain, though the reasons and description of the problems have changed. In addition, we heard everywhere that the key to solving the problem lay with promoting critical thinking and active engagement of students with their subject matter, that rote and passive learning would not work. That is still the message. Indeed, from at least the late nineteenth century, we have heard repeated calls for more active teaching to engage students’ minds and go beyond the didactic approach of lecture and rote memorization.

So where are we now? Reports from the NSF, NRC, AAAS, and others urge over and over that we must teach “science as science is done,” that “science is a way of knowing,” that our goal should be to impart “scientific habits of mind,” and that learning must be learner-centered and oriented toward process. Fine. But what does this really mean for science education, and especially for laboratory education?

First, we must be clear on the reasons for and goals of science education, and one clear theme is that the goals include the desire to promote understanding by all students of the nature of science. Second, we must consider what we mean by the nature of science, addressing the existence of different interpretations of that core concept and including discussion of the role of history in teaching the nature of science. Third and finally come questions about the implications for laboratory teaching: how much, what

sort, and for whom? Addressing these questions includes considering how to draw on our best available understanding of how scientists think and how students learn or the idea of “scientific teaching.” I conclude that teaching the nature of science is central, can be done better drawing on the history of science, and should be part of laboratory work but that allowing all students to experience the nature of science does not require that they every one engage in high level creative laboratory inquiry using modern equipment and techniques. We can promote scientific literacy quite well and fulfill the goals of science education short of achieving that impossibly expensive ideal, and indeed we can better prepare some students to become scientists by not demanding that they all have the same level of laboratory engagement.

Reasons for and Goals of Science Education

Reasons for science education parallel those for all of education, with some variations. They include (not mutually exclusively): (1) developing the perspectives of the “liberal art of science” in order to produce better informed citizens; (2) producing knowledge of basic scientific concepts so that we are a nation of the informed rather than the ignorant; (3) offering hands-on scientific inquiry to promote discovery and to develop scientific “habits of mind”; (4) making available creative laboratory research opportunities to allow high level engagement with “science as science is done.” These are generally offered as parallel to but somewhat different from the reasons for, say, education in art or music because science has become a “basic” and is acknowledged as an essential foundation for economic growth, national security, and progress generally.

Assuming that these are all valid reasons for promoting science education, who is the target in each case? In promoting “science for all Americans,” as virtually all national reports and discussions do, can we really expect to provide every student with all levels and types of science education – or is that even desirable. This is not the place for a full discussion of the role of science in a democracy, nor of differences in cognitive development and learning patterns among students, though both are relevant to the larger discussion. Let us leave it as an open question whether all students should, even in an ideal world of unlimited resources (4) carry out creative research. For now, let us assume that it is at the very least desirable for all students to (1) gain perspective, (2) learn basic concepts, and (3) experience at least some hands-on inquiry.

Reports about the dismal state of American education, such as the National Committee on Excellence in Education’s *A Nation At Risk. The Imperatives for Educational Reform* in 1983, served as a call to action for all educators. That report urged that the “teaching of *science* in high school should provide graduates with an introduction to: (a) the concepts, laws, and processes of the physical and biological sciences; (b) the methods of scientific inquiry and reasoning; (c) the application of scientific knowledge to everyday life; and (d) the social and environmental implications of scientific and technological development. Science courses must be revised and updated for both the college-bound and those not intending to go to college.”(*Nation at Risk*, p. 35)

For science education in particular, the AAAS’s *The Liberal Art of Science. Agenda for Action* provided a call to reform undergraduate science education, including teacher training. *Science for All Americans. Project 2061* appeared in 1990 as the first of a trilogy of AAAS Project 2061 volumes supporting reformed science education.

Discussions of “The Nature of Science” grounded that work, and a core refrain is the importance of promoting “scientific habits of mind.” The message was that we really need to start thinking more like scientists more of the time. In different ways, assumptions about what scientific literacy is, and the assumption that it is good, underpin the NRC’s *Fulfilling the Promise. Biology Education in the Nation’s Schools* that also appeared in 1990, as well as the NRC’s 1996 *National Science Education Standards*. What was meant by “the nature of science” that figures centrally in each of these reports?

Project 2061 explained from the beginning that science reaches beyond the usual descriptions of scientific methods to include science as an enterprise. Accordingly, the following are key elements of the nature of science:

The Scientific World View

- The World is Understandable
- Scientific Ideas are Subject to Change
- Scientific Knowledge is Durable
- Science Cannot Provide Complete Answers to All Questions

Scientific Inquiry

- Science Demands Evidence
- Science is a Blend of Logic and Imagination
- Science Explains and Predicts
- Science is not Authoritarian

The Scientific Enterprise

- Science is a Complex Social Activity
 - Science is Organized into Content Disciplines and Is Conducted in Various Institutions
 - There are Generally Accepted Ethical Principles in the Conduct of Science
 - Scientists Participate in Public Affairs Both as Specialists and as Citizens
- (*Science for All Americans*, pp. 1-12)

The NRC approach in its several reports reveals instructive similarities and differences. The committee that produced *Fulfilling the Promise* about biology education in 1990 did not focus explicitly on the nature of science, but rather on disappointing results from education itself. The report noted that in a 1988 study half the students who

had not taken a biology course did as well or better than 40% of students who had taken a course. (*Fulfilling*, p. 1) The committee articulated the goals of promoting scientific literacy for all, citing education of all citizens as a goal for democracies. They also emphasized scientific literacy as promoting critical thinking and decision-making, and providing a basis for decisions about our natural world. Overall, this report assumes that the challenge is not in defining the goals but in delivering what we take to be good science education, along the way promoting the desired scientific literacy and ways of knowing for all students.

The 1990 NRC report also explicitly addresses the role of laboratories, which few other studies have done. “We are convinced,” the committee wrote, “that instruction in biology that plants the seeds of discovery, awakens students to the beauty of the world around them, and instills some understanding of fundamental biological concepts will serve the interests of most students.” Rather than “obstacles to be surmounted” high school course can be seen as “gardens they have entered.” (*Fulfilling*, p. 72) They lay out core assumptions about laboratories, and it is worth reviewing the reasoning:

The phrases ‘science as a way of knowing’ and ‘science as a process’ carry the conviction that science should be learned by doing. A substantial consensus had developed among investigators of ‘giftedness’ that an environment that encourages inquiry provides the best opportunities for all students to learn (Brandwein and Passow, 1989). The role of the laboratory (as described in Chapter 4) is therefore central to successful instruction; if opportunities are made available to all, students with the appropriate abilities and interests will identify themselves with scientific activities with an appropriate degree of challenge (Brandwein and Passow, 1989). In some schools, it might be possible to provide opportunities outside the classroom and outside the curriculum. That involvement can be especially important in sustaining the enthusiasm of the students most likely to pursue careers in science.” (*Fulfilling*, p. 73)

Inquiry is taken to be good because it stimulates all students to learn. But then laboratories seem important in order to allow those “students with the appropriate

abilities and interests” to take up the scientific challenge. Herein lies our ambivalence as a community of science educators, I suspect. We want to develop a democratic approach that promotes scientific literacy for all, but we also want to provide opportunities for those who might become scientists.

The NRC *National Science Education Standards* as well as the emphasis of Project 2061 is on all Americans, not on just some. What do we need in order to educate all citizens? What scientific content, or knowledge, do we need to teach so that all Americans know whether the earth goes around the sun or vice versa, and in what direction, to pick favorite examples. And what understanding do we need to convey so that Americans are not duped by pseudo-scientific tricksters and superstitions, or how can we keep Americans from inhabiting a demon-haunted world as Carl Sagan put it. Scientific literacy involves both (1) understanding the nature of science and (2) core knowledge – as conveyed in the *Standards*. Furthermore, the authors of all the reports seem to favor, as the NRC committee on biology education did, and at least some (3) hands-on inquiry.

Discussions about the Nature of Science

For this paper, I was asked to comment on two previous discussions of the Nature of Science. In 1996, Brian Alters published “Whose Nature of Science?” Just before the NRC *Standards* appeared, Alters proposed to assess the various existing sets of tenets offered as defining the nature of science (or NOS as he calls it). He offered several pages of lists, then asserted that “With myriad tenets in circulation, the question arises: Who decides for science education organizations and researchers the primarily philosophically

based question of what are the tents of the NOS?”(Alters, p. 42) Not scientists, surely, since they do science but purportedly do not think about its nature as such. Rather, let us appeal to professional philosophers, Alters declared. It is not clear that the Philosophy of Science Association membership, to which he turned is, in effect, the legitimate expert witness as Alters decided to make it. But let us withhold judgment on this question and go along with that assumption. Again, suspending skepticism, let us assume for the moment that it is reasonable to appeal to a professional society of philosophers of science to help define the NOS.

Alters’ methodology relied on a questionnaire developed for the purpose. He concluded from the questionnaire that the NOS is not at all the monolithic or clearly defined enterprise that science educators, and presumably scientists, would have us believe. As a result, we are left without solid grounding for our NOS education standards. Alters concluded that “The implication for the science education research community and its formal organization is that we should acknowledge that no one agreed-on NOS exists.” This is unfortunate since, he noted, “Science education literature and organizations clearly present that the NOS is a major, if not *the* major, goal in science education.” (pp. 48-49) After this rather detailed discussion of analysis of his survey results, Alters concluded with the remarkably inconsequential assertion that “Given this philosophically pluralistic approach, a more appropriate measure of students’ and teachers’ views may be accomplished.” (p. 49). In other words, he ended with nothing as an alternative. Furthermore, he did not argue or even clearly claim that there is no “Nature of Science” but rather that we need “a more appropriate measure of student s’ and teachers’ view” – about what? For what?

Despite its laudable objective of taking on the important question of what we mean by the nature of science, Alters' approach is very disappointing and unconvincing. Even with the most sympathetic interpretation, it is highly problematic. The survey questions are unfortunately annoying because of the misguided assumptions they make. They are so poorly worded that it is possible to answer strongly agree or strongly disagree in many cases for quite different and even conflicting reasons.

Fortunately for science education, two things happened shortly after the appearance of Alters' work. A team of philosophers of science responded with a very sensible and persuasive discussion of Alters' methodology and the implications of his work. Second, the NRC *Standards* appeared and offered its own Nature of Science description, embedded in the discussion of a coherent and cohesive set of standards for science education.

Philosophers of science Juli Eflin, Stuart Glenman, and George Reisch responded to Alters in the same journal. While appreciating the attempt by an educator to understand philosophers of science on the Nature of Science, they concluded that "We believe, however, that his techniques for investigating this question are inappropriate and that consequently, several of his conclusions are unwarranted."(Eflin, et al., p. 107). This rather strong claim has the effect of undercutting the entire project. Challenging Alters' definitions and some of his assumptions, this trio revealed some central errors. For example, Alters relied on an essentialist notion of the Nature of Science. In focusing on extracted "tenets" and seeking to compare them from various works, he was assuming that there should be such tenets and that they should be in conformity if philosophers of science in fact agreed about the nature of science. These authors pointed out, however,

that assuming that there should be such a set of tenets assumes that there is an essence of the nature of science that we ought to be able to find. Rather, they noted that science is more like what Wittgenstein called a “family resemblance.” We do not have to accept Wittgenstein’s particular philosophy to see the wisdom of this point. Rather than difference and divergence, if we look closely at the core ideas about science that each of the authorities Alters had invoked is actually using, there is tremendous overlap. Indeed, there is much more overlap than disagreement, even if there is some divergence in emphasis and choice of language to describe science.

All agree that the goal of science is to acquire some body of understanding that we can call knowledge about the physical world. Science assumes that the world has order, and that science seeks to describe that ordered world in a simple and comprehensive way. Science is dynamic, changing, and tentative. There is no one, single scientific method. Those are the core areas of agreement. All agree that there is no one single method, and certainly not the simplistic almost cartoon hypothetical-deductive method invoked by some science educators and textbooks. Yet this does not mean that science is chaotic and has no method, but rather that it embraces more than one approach and method.

The three authors pointed also to areas of “dissensus,” but felt that these did not undercut the claim that overall the community agrees very significantly about the nature of science. Whether and to what extent the “generation of scientific knowledge depends on theoretical commitments and social and historical factors,” and how much “the truth of scientific theories is determined by features of the world which exist independently of the scientist” raise questions about how science works in the larger world, but they do not

challenge the claim that there is something that we can understand as a basic nature of science.

The authors concluded that Alters' study distorts the vast agreement within the community of philosophers of science. They suggested that "Just as science educators stress that science is more than a collection of facts, we emphasize that a philosophical position about the nature of science is more than a list of tenets." (Eflin, et al., p. 112) Furthermore, they warned against an "overly simplistic pluralism in which all philosophical positions are seen as equally viable" to which Alters' approach might mistakenly lead. (Eflin, et al., p. 114) Where, then, does that leave would-be science educators who would like to get things right? Eflin, Glenman, and Reisch suggested that the AAAS discussion of the nature of science provides a useful "middle of the road approach." They did not, apparently, have access to the NRC *Standards* that appeared about the same time they were writing their article.

NRC *Standards* for History and Nature of Science

In 1996, the NRC issued its *Standards* that quickly became influential in helping states shape their own responses to the national movement's demanding improved science education and also assessment and measuring of success. The importance has only grown with President George W. Bush's "No Child Left Behind" legislation that has pushed states into compliance to national legislation. (see Hollweg and Hill, 2003, for beginning of assessment of impact)

The *Standards* pointed to Content expectations, and also outlined ways to convey the Content so that some of the "content" is actually also or primarily process. For

example, the first Content Standard starts with Unifying Concepts and Processes and states that in K-12 and states that “all students should develop understanding and abilities aligned with the following concepts and processes: Systems, order, and organization; Evidence, models, and explanation; Constancy, change, and measurement; Evolution and equilibrium; Form and function.” The next Content Standard focuses on Science as Inquiry and says that “all students should develop: Abilities necessary to do scientific inquiry; Understandings about scientific inquiry.”

These first two Standards set the stage for all others, and make clear that the intention is to promote student inquiry and to help students think like scientists. This is a decision, and a very worthy one, but nonetheless a decision worth acknowledging. The claim here is not that every student should be able to recognize science from a distance, or should develop appreciation of how science works. No. We have the much stronger claim, as with Project 2061, that all students must experience the inquiry, exploration, and discovery of science itself. Though there is no substantive discussion of the role of laboratories in promoting this process, the pictures show young girls with protective eye gear, obviously in the lab. Clearly the goal is to promote “student abilities and understanding” and not just appreciation from afar. We want a nation that thinks like scientists and in which each child has the skills and abilities to engage in science and not just to watch from a distance and vote support for scientific research.

Content Standard G brings us more nearly to appreciation of the way that science works (or “understanding”), presumably to produce better informed citizens. Here, we learn that “all students should develop understanding of: Science as a human endeavor; Nature of scientific knowledge; Historical perspectives.” The Content Standard here

brings together the History and Nature of Science, with the clear message that we will understand the nature of science better by incorporating history. We need to look both at the Nature of Science as presented here, and also at the claim that the History will inform understanding of the Nature.

According to the *Standards*, the “Nature of Scientific Knowledge” includes that:

- Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, and skepticism, as scientists strive for the best possible explanations about the natural world.
- Scientific explanations must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make accurate predictions, when appropriate, about systems being studied. They should also be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public. Explanations on how the natural world changes based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful and socially relevant, but they are not scientific.
- Because all scientific ideas depend on experimental and observational confirmation, all scientific knowledge is, in principle, subject to change as new evidence becomes available. The core ideas of science such as the conservation of energy or the laws of motion have been subjected to a wide variety of confirmations and are therefore unlikely to change in the areas in which they have been tested. In areas where data or understanding are incomplete, such as the details of human evolution or questions surrounding global warming, new data may well lead to changes in current ideas or resolve current conflicts. In situations where information is still fragmentary, it is normal for scientific ideas to be incomplete, but this is also where the opportunity for making advances may be greatest. (NRC *Standards*)

In short, science relies on empirical methods, seeks explanations based on evidence and confirmation, and embraces change in the face of new evidence and new theories that bring new knowledge. This interpretation is consistent with that proposed by Eflin, Glenman, and Reisch. This is not a pluralism of the sort that “anything goes” but a pluralism that accepts the possibilities of coexisting and even competing theories, experimental approaches, and methods of inquiry at any given time. To be “science” a

claim has to meet certain criteria, but those criteria do hold something of a “family resemblance” and are open to a range of applications. Some explanations and ideas are not scientific because they are not open to the empirical testing of evidence. Some explanations are scientific because they follow the appropriate methods, but not “good science” at the moment because they do not draw on the best available evidence or do not stand up to empirical tests. Science changes over time.

This brings us to the second part of the History and Nature of Science, the History. The *Standards*

use history to elaborate various aspects of scientific inquiry, the nature of science, and science in different historical and cultural perspectives. The standards on the history and nature of science are closely aligned with the nature of science and historical episodes described in the American Association for the Advancement of Science *Benchmarks for Science Literacy*. Teachers of science can incorporate other historical examples that may accommodate different interests, topics, disciplines, and cultures--as the intention of the standard is to develop an understanding of the human dimensions of science, the nature of scientific knowledge, and the enterprise of science in society--and not to develop a comprehensive understanding of history. (NRC, *Standards*)

This approach fits with the assumptions emerging from the literature of the 1980s and 1990s that one of the main reasons students were turning away from science is that it was too difficult, too different, and not something they imagined themselves as doing. By de-mystifying the process, showing that it was done by real people with their own quirks and problems, science education could attract eager young people to think of themselves as scientists. By showing that science changes and develops over time, science education would show that there are many new things to learn and great opportunity for anyone willing to jump in and develop the skills: sort of a “you too could be a Pasteur, Newton, or Madame Curie” (not that anybody should want to be those particular individuals if they really knew about their lives, but we get the point). The

goal was also to make science more of a clearly normal human endeavor, and as the AAAS had said to promote science as a liberal art. This, it was assumed, would make scientifically literate and science-supporting citizens even of those who did not become scientists themselves.

Yet despite the existence of a few history-driven experiments such as Harvard Project Physics, the *Standards* admitted that

Little research has been reported on the use of history in teaching about the nature of science. But learning about the history of science might help students to improve their general understanding of science. Teachers should be sensitive to the students' lack of knowledge and perspective on time, duration, and succession when it comes to historical study. High school students may have difficulties understanding the views of historical figures. For example, students may think of historical figures as inferior because they did not understand what we do today. This "Whiggish perspective" seems to hold for some students with regard to scientists whose theories have been displaced.(NRC, *Standards*)

The NSF has shown little interest in testing the value of history in teaching science, insisting instead of "bench to classroom" emphases, so we still have only limited assessment of the impact of historical approaches. In addition, the *Standards* seemed to suggest that history would primarily be useful in making science seem more human. The AAAS Project 2061 approach is somewhat different, though discussing Chapter 10 of *Science for all Americans* would take us too far astray.

In fact, the greatest advantage of incorporating an historical approach is in showing the necessity of making assumptions at any given time, and in showing the impact of choices made. The Harvard Project Physics approach recognized this and used it very effectively to illustrate by experience of following the reason what sorts of choices scientists have made, that we are all faced with choices and can make better or worse

ones, and that the science is a very human process where some choices are nonetheless better than others – better in the sense of “working.”

This gets us right back to the heart of the Nature of Science discussion. Science gives us method – but a broad and fluid method, with constraints of following evidence, allowing prediction and testability over time, and changing in the face of new evidence. Scientific knowledge changes, and even scientific methods expand and improve.

The ultimate test is “workability,” which also does not have a neat and essentialist meaning but rather a family resemblance and some boundary constraints that help us to demarcation criteria to set off science from non-science or pseudo-science. Observation becomes data becomes evidence, and then evidence in favor or against particular claims. The claims add up to a body of knowledge, so that overall and eventually that body must be coherent and consistent even though at some times there will almost surely be competing and even conflicting claims that are each based on different good assumptions in different specialty areas. A goal of science is to reconcile and coordinate the disparate bits of knowledge, to find areas of overlap and intersection and to find “workable” theories and approaches that allow us to build on the accumulating body of knowledge. Working also means rejecting and replacing ideas when others are demonstrated to fit better with evidence or to be supported by more and more diverse evidence. We should expect scientific knowledge to change, sometimes by growth and sometimes by replacement. We should expect some knowledge to be imprecise, uncertain, and even puzzling. It is the puzzles that lead us to seek different and “better” explanations – better in fitting theory better to evidence, in finding more evidence, in satisfying more and harder tests, and in coordinating different areas of knowledge, for example.

Many discussions of the Nature of Science do falter, as Eflin, Glenman, and Reisch point out that Alters' does, in expecting science to be neat and tidy. Some want science to be neat and exaggerate its neatness, while others want to undercut its claims to neatness and exaggerate the messiness and even insist that science is just another way of knowing with no special value. History shows that neither extreme is defensible. The history of science also shows that it is precisely the untidiness, the trial and error, and the searching for new evidence and new and better explanations that drives scientists and that make science work – but that it does work. Curiosity leads scientists on, and underpins their passion for exploration. Science is a liberal art, one of many. But science is unique in giving us explanations about the natural world that are useful in producing order, predictability, and also potential applications. It is not better or a higher way of knowing about all things, but the best way we have available for explaining and ordering our natural world. Understanding the nature of science also involves understanding that this is a world view and a choice that explaining and ordering the natural world is a valuable thing.

One small example from Arizona illustrates the importance of this standard promoting understanding the nature and history of science. By 1997, Arizona had developed a set of state education standards drawing on the NRC's *Standards* for science but exercising the state's right to move in its own way. The biology standards at first completely omitted evolution, and not accidentally. Fortunately, some astute high school teachers demanded that this be corrected, and the Board of Education appointed a review committee to address just this matter: should evolution be included in the science standards and if so how and why? The Board, and the committee it appointed was split

among those supporting requiring the teaching of evolution and self-declared creationists who were opposed. The NRC's History and Nature of Science became the lifeline for those of us in favor of requiring evolution. We reached enough of a consensus to persuade the Board to accept our recommendations. Along with the basic concepts of evolution, we would add a set of History and Nature of Science Content standards. These emphasized that science involves weighing evidence for and against theories – all theories, all the time.(Arizona Standards)

We did not allow the creationists to single out evolution and demand that all teachers and all students study evidence for and against evolution, which would have opened the door to requiring “scientific creationism” in the classrooms. Rather, incorporating the NRC standard allowed us to enable teachers and students to engage in discussion of “evidence” and what counts as evidence, as well as how evidence weighs in favor or against theory – any theory, all theories. This approach passed, and it has prevailed again when Intelligent Design creationists just this year tried to remove evolution and to insert language requiring critique specifically of evolution. We pointed out, once again, that we have the History and Nature of Science standard that already serves as a sort of “macro” program to be applied to all of science. There was no need for a special standard requiring all students to learn “evidence against evolution” as they proposed in 2004. In addition, pointing to history and the changes over time shows that what is known today may change tomorrow. Perhaps oddly, this has given creationists hope that their preferred view will come back to prevail again, rather than leading them to the conclusion that their preferred theory has long been replaced.

The lesson here is that by honestly incorporating the History and Nature of Science discussion, and by letting students see that science as well as individual scientists have warts and idiosyncracies, we strengthen commitment to science. Had we adopted the approach recommended by many in the scientific community, namely just demanding that creationism is not, cannot be, and must not be allowed to be presented as science, we would have polarized discussions further. We would also have given the message that science and scientists are dogmatic and doctrinaire. And that is precisely what science is not, or should not be. History reveals the complexity and competitions within science, and we need to make those more visible and more acceptable in science education. Science is a way of knowing, indeed. A way that leads down blind alleyways, that twists and turns and makes mistakes, that allows for something nasty and heated competition and disagreement within the ranks. Great! Science is a process of innovating, sorting, testing, and advancing our evidence and our explanations. That's the nature of science and what we should be teaching all of our students.

Laboratory Discovery for how many and which Americans?

Now we return to the question how much of (4) laboratory-based inquiry or how much creative opportunity with modern equipment and techniques is right for all Americans? Does everyone need to experience science labs any more than each needs to play a musical instrument or participate in studio art? Should this be a goal for every student, or for just some, and if for only some then for which and according to what process of selection? We all know the risks in not demanding equality, by which it is safest to mean the same, for all. But we do not insist on football for everyone, or

trombone or sculpture. In too many cases, we leave such “electives” to those who can pay, but we also make selections for those with perceived “talent” or commitment in an area. There seems to be little solid research grounding claims in this area.

At Arizona State University, we have adopted a pyramid scheme, so to speak. It works well and may provide a useful model for high school education as well. For scientific inquiry through laboratory experiences, at the base we provide introductory experience for all. Every student who takes a course in the life sciences (and the same holds for the other sciences at this level), engages in inquiry-based laboratory exercises. Rather than the old-fashioned “guess the right answers the lab is intended to give you” approach, these labs have been modified with the help of substantial HHMI and NSF support to ask “what if” and “how come” and “what do you see and how might you explain this and persuade your fellow students of your team’s explanation?” Open-ended, inquiry-based, learner-centered, discover-oriented, and all that. Every student gets this introduction in the non-majors as well as majors introductory courses.

In the second tier of the pyramid, we select a smaller number of students to work in lab or field projects, and to date we have managed to include all the really qualified students who have wanted to participate. These students are the “apprentices,” working alongside the grad students, postdocs, and faculty members in the university and in research centers around the Phoenix area. They are paid an hourly wage and receive mentoring and training through the individual lab and through the program, learning about bioethics, policy, and research practices as well as lab techniques. For a mentor to receive support for a student through the program, the lab must agree to include the student in regular lab discussions and to assign independent work. While everyone may

help washing test tubes, running tests, and such, a lab will not receive an apprentice funded through this program without agreeing to give other inquiry-oriented opportunities. These students present posters to summarize the lab's work, and they are trying on what it means to be scientists even though they may intend careers in medicine, policy, writing, teaching, or other areas as well as the sciences.

What these students do sounds very like what some of the science educators propose for all high school students, but there is absolutely no possibility that we can create such supervised quality opportunities for all of even our 1800+ life science majors every year, much less for all the tens of thousands of undergraduates at ASU. We believe that this pyramid approach makes sense and leads some students on to higher levels of achievement than we could produce if we tried to do more with more of them. We prefer a philosophy of promoting each to "Be all that you can be" rather than demanding that "No child be left behind" since that latter has the implication of holding some back while the stragglers catch up. Different goals for different students makes sense.

At the top of the pyramid, we have Research Fellows. These students are provided with an annual stipend and are expected to carry out increasingly independent projects as well as to study science communication and to present their results at national meetings and to begin publishing. This group then provides a cohort of senior mentors and role models for the introductory students. We are just beginning to implement peer mentoring, with the goal of inspiring more and a more diverse group of individuals to take up science. Most of this group intends to pursue careers in science or medicine.

It would make sense to consider such a pyramid approach at the high school level as well. What can we provide for all students, those who have little interest in science

but whose imaginations we can tickle if we do it right and those who we can engage in inquiry through often simple exercises. What makes something bubble when it's hot, why does a ball dropped while you're walking not fall straight down, why does the wind blow the direction it does, what makes something explode, why can a genetic gel convict a criminal, etc.

“Scientific Teaching”

What does this mean for science education? Let's focus on the top of the pyramid, on those who may become scientists and for whom we want them to have the highest level of interaction with science. Maybe the argument will prevail that this should be all Americans, and maybe we will agree to offer this level of education for some. Whichever we choose, what should we do for them? Jo Handelsman, et al., argue in *Science* that the education community needs to take up “scientific teaching.” As they point out, their arguments and suggestions are not new, but the academic community has been too slow to take up reforms that the education community has acknowledged as needed, and “This Policy Forum is needed because most scientists don't read reports but they do read *Science*.”(Handelsman, et al., 521-522) They call for university faculty leadership in reforming science education at all levels to provide the opportunity inquiry and engagement that every report recognizes as important. And they point to examples and web materials to help make it happen. We need more move in this direction, and as they note more recognition for those who do take up the challenges. I would argue that we need for leaders such as NSF to be more creative in the projects they support as well, but fortunately there are other groups and foundations available to help.

We also need much more research on cognitive processes, learning, and how scientists work. Kevin Dunbar, for example, calls for more study of scientific thinking. How do scientists think, and how can we make those approaches part of science education, he asks. Scientists will follow up on surprising results, engage in analogical reasoning, work in teams with distributed reasoning, and have to remember to expand their goals to pursue surprises and follow paths not originally imagined.(Dunbar, p. 57)

In sum, we need additional materials and assessment of success using those materials. Not just materials for teaching science content, and not just for promoting inquiry, but also for addressing the nature and history of science as part of science education.

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