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Science Literacy: a More Fundamental Meaning

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Over a century of attention to "science literacy for all" has not produced a public that can appreciate a common body of core science facts, concepts, and methods; nor have many acquired from their years in K–12 education the ability to apply science learning to everyday problems or to the scientific issues that concern a democracy. Some have called the endeavor impossible and moved on to lesser goals of science appreciation and heuristic guides to choosing trusted experts. However, a route to science literacy may yet be possible, if we redefine the goal as achieving literacy within a community. The tools for that end are different from what is generally offered in the classroom. What will be more helpful is a set of core values that underlie the generation of science concepts and facts, that inform the methods of science, and most importantly, that enable the social interchange that is the essence of the scientific endeavor. These values—the ethos of science—should be offered to elementary school students as a culture that forms through inquiry into questions students bring with them from their own experiences. Suggestions are offered as to how this might come about, with the central role occupied by the teacher as model and with the culture nurtured by the teacher, by a practitioner from the world of science, and eventually by the energy and contributions of the students themselves.

KEYWORDS science literacy, Mertonian norms, primary school, skepticism, inquiry, mentoring

PERSPECTIVE

Meaning, goals, and benefits of science literacy

In the 30 years that I directed biology-related courses at universities, I placed as a central goal science literacy, as I conceived it. In some sense, many students came to the university highly literate. When requested, they could bring forth no end of scientific facts. But science literacy in a more fundamental sense was rare. Using their knowledge in creative ways and distinguishing what part of it was actual observation and what was only plausible assertion was generally beyond them. They knew nothing of ignorance and confusion, which are central elements of scientific discovery (1, 2) and so wilted at their approach.

What is the most useful meaning ascribed to "science literacy"? What are its educational goals at which we should aim? What perceived benefits animate those goals? There is little agreement in these matters (despite the air of certainty found in some reports). The various meanings of science literacy have been explored by many (e.g., references 3–6). Below, I describe two influential meanings of the term.

Science literacy as essential facts and concepts

One frequently articulated educational goal is that each scientific discipline should provide all students with a coherent set of facts and concepts through which to view the physical world (4). This is the meaning of science literacy adopted by the Next Generation Science Standards and the National Research Council report on which they are based (7, 8). The discussion has generally focused on the majority of students, i.e., those not bound toward careers in science. How might they benefit from the considerable time needed to achieve this goal? A widely cited taxonomy of perceived benefits (9) listed three classifications: (i) practical (e.g., helping the individual to address health issues), (ii) civic (enabling citizens to address meaningfully public issues with scientific content), and (iii) cultural (appreciation of science as a major human achievement). Are these potential benefits realized through science literacy?

It is commonly presumed that learning scientific facts and concepts will achieve these benefits among the lay public (8, 10), but there is little research that bears on the question (11), and it is debatable whether the classroom products of science literacy education are readily transferable (12) to everyday practical problems (6, 13, 14). A rare study that attacked this question directly (15) reversed the usual order of inquiry (11) and asked, "What are the needs of people confronting everyday problems?" That study found

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that everyday science-related problems confronting lay people seldom required knowledge they might have been taught in school. Instead, the problems called more for a sense of how science works, with intrinsic variability in measurements, the need for exploring alternative explanations, etc.

Similarly, the claim that civic science literacy facilitates citizen participation in the issues of the day has little or no evidence to support it (16). One might expect that increasing science literacy in citizens would lead to more common ground on scientific issues. Instead, high levels of science literacy (as judged by factual knowledge) are associated with more extreme polarization on issues (17). A shared set of learned scientific facts seems not to dispel the politicization of science-based issues.

Science literacy as habits of mind

A more fundamental view of science literacy goes behind core science facts and focuses on the minds that use them. Suppose that Galileo were somehow transported to our times, into a high school class, and confronted with the standard 10-question factual knowledge test (Science and Engineering indicators) used by the National Science Board to assess scientific knowledge (3). Galileo would have known only one of the expected answers (related to the heliocentric solar system). But if our educational system produced graduates with the mental tools of Galileo, that would be a victory of the highest order. Galileo could learn whatever facts were required as needed.

Recognizing this, some of the early writers on science education for all lauded the study of science for its ability to cultivate the mind (4). For example, Thomas Huxley wrote of the ability of science to teach students to bow to no authority short of Nature herself (18). Karl Pearson described the scientific frame of mind as one that operates apart from personal feeling and emphasized that it is within reach of everyone (19). By the second half of the 20th century, the desired habits of mind had become less mental states and closer to scientific practices, such as controlling variables (4). Students were encouraged to "think like scientists," using a scientific method that had grown ossified through pedagogical use (4, 20).

IS SCIENCE LITERACY AN ATTAINABLE GOAL?

In the 1990's, several researchers came to the conclusion that science literacy for all could not be achieved under then-current definitions (5, 21). Morris Shamos wrote, ". . .the notion of developing a significant science literacy in the general public. . . is little more than a romantic idea" (5). Shamos was equally dismissive of the possibility that many students could achieve scientific habits of mind (5).

Others have confronted the same inefficacy of science literacy but come away with different solutions (6, 11). Noah Feinstein pointed out the lack of evidence supporting the purported benefits of science literacy. He then turned around the question of what must people know to be scientifically literate, asking instead, "What does science literacy look like?" (11). In some case studies, it looked like students bringing their varied lives into school science (22). In others, it looked like a community that draws on a collective science literacy to address issues of intense interest to the group (23). There are many such examples (3). Feinstein viewed these lessons as pointing toward a way that science literacy for all, if redefined, could be achieved.

This discussion echoes one that took place almost a hundred years ago. The Lippmann-Dewey debate (24) explored what role a public in a technological democratic society is able to play in determining policy. Walter Lippmann, one of the most influential journalists of the 20th century, argued that mechanized society had progressed to the extent that the layperson could not possibly exercise a meaningful voice (25, 26). On the other side was John Dewey, who agreed with Lippmann regarding the limitations of individuals (27). However, he envisioned a "democratically organized public" imbued with a "diffused and seminal intelligence" that through productive interaction could participate meaningfully in addressing the technological issues of the day (28). By "public" Dewey did not mean nonscientists or society at large but rather a participatory community with shared interests (24). We might now call the diffuse intelligence of a public group "science literacy" (3).

What role can schools play in building the capacity of students to engage in group science literacy? The purpose of this Perspective is to address this question, choosing the optimism of Dewey and Feinstein over the pessimism of Lippmann and Shamos.

A ROUTE TOWARD SCIENCE LITERACY FOR ALL

The ethos of science

Devising an educational experience that promotes science literacy for all may be possible, despite the evident lack of success thus far, by embracing a more fundamental meaning. Science literacy has been presented as following one of two visions (29). Traditionally, literacy has focused on the crystalline logic of disciplinary science and bringing its achievements to the minds of students (Vision I). Alternatively, the focus might be on societal problems and the role of science to address them (Vision II). Paradoxically, students may gain greater capabilities within both visions if we put both aside and focus student interactions instead on the underpinnings that make possible the human scientific endeavor, the ethos of science. After briefly describing what I mean by this term, I will present a strategy to create a community of inquiry that engages elementary-age students in the ethos of science. Similar ideas have been discussed elsewhere (30–32) and realized (33).

Our understanding of the ethos of science—the seldom-expressed framework for scientific society—has been shaped by the highly influential formulation of Robert Merton (34) (recast more succinctly by John Ziman [35]). The ethos is encapsulated in the norms of science described below, which we can see is not a description of how to do experiments, but rather a blueprint for how to interact within a scientific community, without which there is no science (21). The four norms are the following.

Communalism: the fruits of scientific discovery belong to all. Every observation implies an observer, but once the observation is presented to the community, it belongs to everyone. Hypotheses as well are gifts to the community. There are no "my hypotheses", just "hypotheses", which we should all hold at arm's length.

Universalism: what counts is the idea, not the person who voices it. According to the Norm of Universalism, status does not matter. When Watson and Crick went head to head with Linus Pauling to determine the structure of DNA, it didn't matter that Pauling was probably the most respected chemist on Earth, while Watson had just one obscure publication and Crick was still a graduate student. Watson and Crick's idea (36) was accepted for its ability to explain nature, while Pauling's (37) was not. Nature, not human authority, is the ultimate arbiter of truth.

Disinterestedness: what matters is not what you want but what Nature says. There's no end of bias in science, the same as in every human endeavor. The Norm of Disinterestedness calls on us to look for bias within ourselves as best we can and root it out to the extent possible.

Skepticism: don't believe it until you have no choice. Of course people who do science are skeptical! But it does not follow that all is to be doubted. Observations are taken as truth (provisionally), but statements that go beyond observations are suspect. The Norm of Skepticism is practical, like a person climbing the face of a cliff. You reach for a rock that theory says is supposed to be okay. You're not so sure, so you test the rock gingerly. It seems to be solid, and you make your move, but you're still not completely convinced. Maybe if the temperature were much higher, that rock wouldn't hold.

It does no good to point out that scientists often fail to live up to these norms. Followers of a religious faith often do not live up to its tenets, and yet those tenets still possess considerable power, even over those who fall short of them. In the real world, we're all attached to our own ideas and stuffed with bias. It is the same within a community governed by the ethos of science, but we're not proud of our deviations and are expected to work to overcome them. The norms provide a structure that more often than not enables productive discussions and collective movement to a closer alignment with reality.

Building scientific communities in the elementary school classroom

I have focused on elementary school children for many reasons. We are born as highly skilled practitioners of science (38, 39), capable of exploratory learning (and with more wonder and less bias than adults) (40), and by grade school we are capable of skepticism of adult claims (41). However, interest in science wanes as people progress through K–12 education, reaching very low levels in high school (6, 42, 43). In my many years directing classes at the university level, I have tried to build communities consistent with the ethos of science, but it is not easy. Many students, particularly the most academically successful, are heavily invested in the strategies that have gotten them high grades, strategies that are not consistent with scientific inquiry (44). It is easier to bend a young branch.

Needless to say, no branch would be bent by subjecting elementary school students to scholarly discourses on the ethos of science. It must be learned the way any culture is learned: by living within it. Accordingly, I suggest that elementary school classes form communities of inquiry modeled by teachers (see below) that address questions that appeal to groups based on their diverse experiences (12, 45), with time for research interspersed with explicit discussion of the principles of the research community and of effective research (46). A National Research Council report made a persuasive case for setting inquiry-based learning at the center of K–12 science education (45) (though it didn't persuade everyone) (47). Inquiry based on student-generated questions, in its various flavors, offers many benefits, including the most characteristic: encouraging the formulation of questions, a key component of science literacy (48, 49). The freedom to form one's own research questions, with teacher guidance, is well liked by elementary school students and is motivational (50), particularly when students can form connections between questions, their lives, and their communities (12).

It is true that children do not do science the same way as professionals, but neither do they learn language the same way as adults, and it would be insanity to insist that they do so. The goal is not to recreate in them the mind of adult scientists nor the conceptual toolboxes of laboratory research, much less their disciplinary body of facts. The goal is to entice students into a community that is engaged in problems meaningful to them, the greatest source of intrinsic motivation (12), and one that engenders self-efficacy, the greatest assurance of lifelong engagement (51). This they can take with them through later grades, a framework in which to place what they learn from school science. This, more basic than facts, they may retain throughout their lives.

A taste of method

Students will not study Merton's philosophy directly. Instead, they will encounter it at first through the examples of their teachers, most obviously through the slogan "How do you know?," a proxy for the Norm of Skepticism. I have introduced this to university sophomores and juniors through a line-by-line dissection of the poem, *Mary Had a Little Lamb* (this example can be used in a K–5 classroom without modification.). I break them into groups to discuss which utterances are observations or reports of observations (and therefore to be trusted) and which are merely conclusions, a surprisingly difficult distinction (52). Little? How do you know? What might actually have been observed? "Had a little lamb"? How do you observe that?

The lesson is pressed home by a game inspired by the well-known tale of blind men feeling an elephant (53). The game starts with each person assigned one of four newspaper articles concerning the efficacy of vitamin D in the elderly (54–57). On the surface, the articles seem to contradict each other. However, if the students ask each article, "How do you know?," the answer lies in the research articles on which the news articles are based (58–61). Each student examines the research article underlying the assigned newspaper article and shares insights with a group of four, each student assigned a different article. If we all live in the same universe and the observations in the research articles are true (as they are presumed to be), then they should be compatible with each other, despite the newspaper headlines drawn from them. As it turns out, one experiment measured vitamin D levels in patients presenting with broken hips, while another monitored the incidence of fractures in people given vitamin D supplements. One experiment specified 800 units of vitamin D twice daily, while another specified 100,000 units once a month. And so on. When the groups reassemble as a class, we discuss whether the observations are compatible, even though the conclusions are not.

That is how it plays out at the university level, and I'm convinced it could work equally well in high school and middle school classes. For K–5 students, however, a more physical realization of the metaphor is no doubt required. The class could be presented with a black box with four holes. Entering each hole is a long rubber glove, rendered immobile except for its fingers. A student who tries the first glove might describe feeling a large coin (or a hard smooth circular surface), another trying the second glove might describe feeling a grape (or something small and squeezable), a third might describe a hose (or a flexible, long cylinder), and a fourth a pail handle (or a hard, smooth, inflexible arc). After groups try to combine their observations into a single drawing and the drawings of each group are discussed as a class, the box is opened, to reveal a stethoscope.

Another game is to offer students the four panels shown in Fig. 1, invite them to write down briefly what they see in each panel, and then to place the panels in temporal order. No controversy here; everyone agrees on the order. Then I assign each group an arbitrary order of letters (say, BADC), tell them that this is the true temporal order, and encourage them to devise plausible sequences of events that explain that order. For example, in some cultures, races might traditionally begin by having runners stand in separate blue boxes and end by bowing toward a racing official. Each group shares its interpretation (often quite creative), initiating a discussion on how bias affects what we think we see and how a second slogan, "How do I know?," can serve as a partial defense (and, not stated, a route to the Norm of Disinterestedness).

The group is given an explicit framework for productive discussions (62). In brief:

- The norms of science remain in force, especially the Norm of Disinterestedness.
- The purpose of discussion is discovery, not victory. The unit of discovery is us, not me.
- Everybody plays. Everyone has something to offer.
- Everybody's fallible. No matter how passionate you are about a position, you may be wrong in some particular. That confession is a necessary prerequisite for discussion.

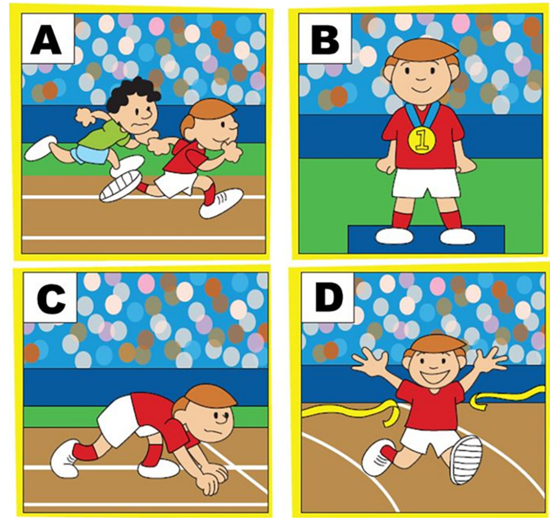

FIG 1. Unordered images used in introduction to bias. Students are invited to write down what they see in each of the four images and then, to place them in a logical order, an illustration of the norm of disinterestedness. See text for description of use. The panels were modified from an image from All Kids Network (https://www.allkidsnetwork.com/sequencing/sequencing-worksheet-race.asp), with permission of the publisher.

- All ideas are worthy. Every point raised deserves a meaningful response before moving on.

Supporting teachers in their central roles

This community, if it comes about, will do so through the skill of teachers (63). But how? A variety of studies have indicated a general low self-efficacy in elementary school teachers with regard to science, important in part because of the relationship between teachers' self-efficacy and their willingness to try different teaching strategies (reference 64 and references cited therein). Furthermore, teachers have lived far longer in our society than their students and therefore have accumulated far more cultural baggage to set aside, e.g., that reading something makes it so, that discussion is a blood sport, and so on. And all of this lies on top of a common fear of inquiry methods (44). The solution, of course, is for teachers to absorb the ethos of science the same way as their students, by living it. Ideally, teachers, as part of their professional training, would experience research first hand within a scientific community (65) (if only that were scalable). Extended professional training is certainly to be desired (66), but for the moment, it is necessary to resort to stop-gap measures. I do not believe professional development sessions would be enough to bring teachers into the ethos of science, nor would 2-week summer institutes (30, 67). Then what?

Students learn culture in school from models, primarily their teachers. Teachers new to the ethos of science may also profit from models. Since 2013, a program, Savanturiers, has paired mostly primary school teachers with active researchers to aid the implementation of student question-based inquiry

(68). There are other programs that overlap to some degree (44, 69). Even experienced teachers have appreciated the collaboration of a research practitioner before trying out inquiry-based methods (44).

A major constraint on the Savanturiers program has been the limited number of researchers willing to participate (68). Scaling up such a program to meet the needs of a large number of elementary schools would be difficult to imagine. However, there is an alternative. We are in the midst of the period in U.S. history when the baby boom generation will reach 65 years of age, accounting for 15% of the population in 2016 and increasing to 21% by 2030 (70). There may be a significant supply of retired researchers who are enthusiastic about interacting with primary school teachers and students on a regular basis. At least two programs that pair retired researchers with K–12 teachers have cropped up over the years (71, 72). Both programs, which engaged those coming from careers in science or engineering, were aimed at middle school and high school classes, and neither had any specific pedagogic goals besides placing the retired researcher at the service of the teacher.

I propose extending the idea of teacher-retired researcher pairings. The researcher would agree to interact with the teacher and the class over the course of a semester for at least 2 h per week, but before this could happen, a significant amount of orientation and training would be required to make the pairing work as desired. The teacher (and later the students) may initially view the researcher as an all-knowing fount of knowledge, i.e., an Other (66, 68, 73). The Norm of Universalism should be invoked from the start. Researchers have no claim to authority beyond the occasional alignment of their ideas with reality. The primary role of the researcher is to model the ethos of science and to ask a lot of questions: How do you know? How do I know? How can we find out? Effort will be required to impress this role on volunteer researchers.

RETROSPECTIVE

One way to think about different views of science literacy is according to their depth of focus: (i) the relatively superficial, i.e., acquaintance with certain core scientific concepts; (ii) the more fundamental, i.e., the mental processes used by those who do science for a living; and (iii) the most fundamental, i.e., the ethos of science, the environment within which those mental processes were developed and those core concepts were conceived. The goal of the latter view of science literacy is immediate: to introduce students into a community of science that is seen by its members as powerful, right now.

What about long-term goals? How will students use this form of science literacy as adults? We can't know. Neither can we know how the student will eventually use the ability to read. We do not concern ourselves much with that topic, because reading literacy is so obviously a powerful tool, the birthright of us all. So is science literacy in the sense described. An adult may use it to bask in the brilliance of scientific achievement or to influence public policy or to engage with ideological critics in productive discussion; that is not for us to decide (74). But what is on us, as a society, is whether the student-soon-to-be-adult is offered this second birthright, the power that comes from the mindset that enables the scientific enterprise.

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