

A Science Education that Promotes the Characteristics of Science and Scientists

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Editor's note: This article is the first of four in a series written by Michael Clough regarding the nature of science, and how it relates to STEM education. The next three will appear in subsequent issues.

INTRODUCTION

Why does anyone do science? Why would anyone *want* to do science? Those are questions that take on added significance as policymakers around the globe emphasize the importance of STEM education and seek to encourage the best and brightest young minds to enter STEM fields. But at the root of those questions are more fundamental issues that are important for all citizens. Two such questions are:

1. "What is science?" and
2. "How is science different from, but related to other STEM fields?"

Understanding the characteristics of science, what it is and how it works, will convey much about the characteristics of people who do science. And that will assist in understanding why science is a career worth pursuing, a field of study worth following long after one's formal education ends, and a human endeavor worthy of public support.

Characteristics of Science and Scientists

What science is appears straightforward, almost obvious. However, students and the general public have significant misconceptions about what science is and what drives many scientists. Some have said that science is simply what scientists do. But that doesn't really clarify the situation, and it clearly begs the question "What then do scientists do?" Many people, including far too many policymakers who ought to know better, often sell science and scientists short by placing a technological end-product as the primary, if not sole, reason for doing science. While some scientists do focus their research on an aspect of the natural world that has implications for solving a societal problem, Neil deGrasse Tyson (2011), an astrophysicist and popular science communicator challenges this view of why most scientists devote their careers to doing science:

This notion that science is the path to solve your problems, I think that misrepresents what drives scientists. Do you think when you speak with Brian Green he's going to say I am trying to come up with a coherent understanding of the nature of reality so that I can solve people's problems? Do you think that's what driving him? Do you think I'm being driven when I look at the early universe or study the rotation of galaxies or the consumption of matter by black holes, do you think I'm being driven by the lessening of the suffering of people on Earth? Most research on the frontier of science is not driven by that goal—period! Now, that being said, most of the greatest applications of science that *do* improve the human condition come from just that kind of research. Therein is the intellectual link that needs to be established in an elective democracy where tax-based monies pay for the research on the frontier. ... the purpose of science is to understand the natural world. And the natural world has, interestingly enough, built within it forces and phenomenon and materials that a

whole other round of clever people, engineers, in the case of the magnetic resonance imager, these are biomedical engineers basing their patents and their machine principles on physics discovered by a physicist, an astrophysicist at that. So I take issue with the assumption that science is simply to make life better. Science is to understand the world. Now you have a utility belt of understanding. Now you access your tools out of that, and use those, that ever increasing assortment of power over nature, to use that power in the greater good of our species. You need it all.

Edward Teller, a theoretical physicist who played a significant role in the development of the atomic and hydrogen bombs, also acknowledged that “The science of today is the technology of tomorrow”. But in the statements by both scientists is the clear indication that science and technology, while sharing many characteristics and being closely allied, are not the same. As a starting point for coming to understand the characteristics of science and scientists, consider the following statements about science and its nature:

Man loves to wonder, and that is the seed of our science. *(Ralph Waldo Emerson)*

Science is first of all a set of attitudes. It is a disposition to deal with facts rather than with what someone has said about them. *(B. F. Skinner)*

Every grand advance in science has issued from a new audacity of imagination. *(John Dewey)*

Science is not a technique or a body of knowledge, though it uses both. It is rather an attitude of enquiry, of observation and reasoning with respect to the world. It can be developed, not by memorizing facts or juggling formulas to get an answer, but only by actual practice of scientific observation and reasoning. *(K. T. Compton)*

Science is a method for testing claims about the natural world, not an immutable compendium of absolute truths. *(Stephen. J. Gould)*

In science, imagination is more important than knowledge. *(Albert Einstein)*

If we knew what we were doing, it wouldn't be called research. *(Albert Einstein)*

Albert Einstein said a number of profound things about science. But one of his often quoted statements that “The whole of science is nothing more than a refinement of everyday thinking” is often misunderstood. He certainly *wasn't* saying that science is merely common sense. In fact, science ideas often appear counter-intuitive, and are only understood by *abandoning* our everyday interpretation of events! For instance, consider the dissatisfaction expressed by the following very bright physics student after having been taught about Isaac Newton's first law of motion:

What is this game that scientists play? They tell me that if I give something a push it will just keep on going forever or until something pushes it back to me. Anybody can see that isn't true. If you don't keep pushing, things stop. Then they say it would be true if the world were without friction, but it isn't, and if there weren't any friction how could I push it in the first place? It seems like they just change the rules all the time. (Rowe and Holland, p. 87)

This student, using everyday common sense experiences with objects, rejected the well established science idea that objects in motion (or at rest) will forever remain in the same state unless acted on by another force. The idea Newton proposed is clearly counter to everyday common sense experience, and this accounts for why his crucial insight originated in the 17th century, even though humans have always observed the motion of bodies. The statement about motion that Newton put forth, and the idealized conditions underpinning that statement about the motion of objects, illustrate how scientific thinking often demands letting go of common sense thinking in order to understand how the natural world works (Wolpert, 1992; Cromer, 1993; Matthews, 1994; Pinker, 1997; and Toulmin, 1972). Doing science often requires a conscious effort to avoid everyday common sense thinking, and imagine possible ideas that underlie what is observed.

Taken together, the overview above illustrates that science is clearly a human effort to understand how the natural world works. Science demands a multitude of approaches that require ingenuity, creativity, reason and perseverance. What results is knowledge about the natural world, but that knowledge is the product of science, not science itself. Furthermore, that knowledge, no matter how well established, can change as scientists continue their work and come to better understand the natural world. We never know if we have the absolute truth of the matter, but we may nonetheless move forward knowing that such knowledge is reliable and forms the basis for much of our modern technology.

Scientists, we must remind ourselves, are first and foremost people who share an intense curiosity about how the natural world works. They ask questions about aspects of the natural world, and find thinking about and solving nature's puzzles very rewarding. Some choose research areas because of an interest in helping solve some social problem, but most are primarily interested in understanding the mysteries of nature. Beyond that, common characteristics of scientists include perseverance, creativity, and valuing collaboration in solving problems. In other words, scientists share many characteristics with those in other fields of study, but their efforts are directed at understanding the natural world. Scientists, justifiably, take great pride answering a question put forward about nature. But just as life is a journey filled with temporary destinations that serve as launching points for other journeys, science is a process that produces knowledge, which in turn raises questions that form the basis for new journeys. The enjoyment of science is doing science, a point that school science must always keep in mind and cultivate among students.

Characteristics of Technology and Those Who Create It

While science is directed at *understanding the natural world*, technology is about *modifying the world* in a manner that extends human capacities to achieve a desired end. Technology entails much more than the electronic devices that many people think about when asked to provide examples. Any artifact that extends human capabilities—such as vaccinations, steel, paper, writing utensils, language, and even the alphabet—is a technology. But technology consists of more than objects invented by humans. Technology also includes the knowledge, processes, and systems that produce those objects. Technology even includes procedures developed to impact human action (e.g., bus routes, emergency evacuation procedures) because although they are not physical objects themselves, they do extend capabilities.

Technology, like science, is a human endeavor, but one directed at modifying the world, not understanding how the natural world works. That said, technology and science as well as all STEM fields share an important overarching feature. They all involve iterative cycles of creating, expressing, testing and revising ideas. Not surprisingly, those who create technology share many characteristics with those in other STEM fields. However, despite these overarching similarities and the extensive interactions among STEM fields, they are not alike in all ways. A robust science education, in addition to making clear how intricately connected STEM fields are, would also make clear how science is unique, the intrinsic value of scientific knowledge, and the crucial role scientific knowledge plays in STEM efforts.

Goals for Science Education

School science has many purposes. Preparing students for science and STEM-related careers is certainly one of those many purposes, but a truly meaningful and effective science education would also accomplish far more noble purposes. It would persistently and earnestly engage students in a manner that models and promotes action resulting in attitudes, understandings, and skills that make for a well educated (as opposed to trained), self-actualized, caring, curious, motivated, responsible and reflective human being. The goals in Table 1 reflect these noble purposes for school science as well as the desire to

prepare students for STEM and STEM-related careers, and they are congruent with desired outcomes for science education appearing in United States (AAAS, 1989 & 1993; NRC 1996, 2000 & 2013) and international science education reform documents. Achieving these goals would also more accurately convey what doing authentic science is like, and when school science does this, students generally find science and science courses more interesting (Arya & Maul, 2012; Hong & Lin-Siegler, 2012) and thus are more likely to consider science and STEM-related careers.

Table 1. Goals for Science Education

- Demonstrate deep robust understanding of fundamental science concepts.
 - Exhibit an accurate understanding of the nature of science.
 - Exhibit an accurate understanding of the nature of technology and engineering.
 - Identify and solve problems effectively.
 - Be creative and curious.
 - Use critical thinking skills.
 - Use communication and cooperative skills effectively.
 - Actively participate in working towards solutions to local, national, and global problems.
 - Set goals, make decisions, and accurately self-evaluate.
 - Access, retrieve, and use existing scientific knowledge in the process of investigating phenomena.
 - Convey self-confidence and a positive self-image.
 - Demonstrate an awareness of the importance of science in STEM and STEM-related careers.
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Critics often argue that time doesn't exist for promoting goals outside of understanding the content of science. These skeptics fail to notice that developing a deep and robust understanding of scientific knowledge demands learners use critical thinking skills, understand the nature of science, engage in understanding the significance of scientific problems and strategies for solving those problems, assess proposed solutions, and exhibit other characteristics associated with the goals above. The deep and meaningful understanding of science content that we want in our students follows from the active engagement with content reflected in the goals listed in Table 1. And the characteristics reflected in those goals are congruent with the work of those engaged in STEM fields, and will serve *all* students.

SCHOOL SCIENCE FALLS WELL SHORT OF DESIRED OUTCOMES

In *Never Playing the Game*, Yager (1988) chastised school science instruction for rarely permitting students to conduct investigations that are even remotely authentic, to create and defend research designs, analyze data, draw conclusions, and formulate possible explanations—that is, to actually play the game of science. He wrote, “We pronounce science a fantastic game—that all should learn to play it. ... [But] our students rarely get to play—rarely get to do real science . . .” (p. 77).

The persistent findings from research in science classrooms reveal a failure to take seriously what is well understood about how people learn (Bransford, Brown & Cocking, 2000) and implement teacher decision-making and actions that engage students in conceptually wrestling with science ideas (Weiss, Pasley, Smith, Banilower & Heck, 2003). Unfortunately, what Goodlad (1983) wrote almost 30 years ago continues to describe the problems we see today in science instruction:

One would expect the teaching of social studies and science in schools to provide ample opportunities for the development of reasoning: deriving concepts from related events, testing in a new situation hypotheses derived from examining other circumstances, drawing conclusions from an array of data, and so on. Teachers listed those skills and more as intended learnings. We observed little of the activities that their lists implied, and teachers' tests reflected quite different priorities— mainly the recall of information. The topics that come to mind as representing the natural and social sciences appear to be of great human interest. But on the way to the classroom they are apparently transformed and homogenized into something of limited appeal (Alfred North Whitehead's words on the uselessness of inert knowledge come to mind) (p. 468).

The manner in which science is commonly taught, and the rapidity that content is plowed through results in the mile wide and inch deep curriculum, and conveys the unmistakable image to students that scientific knowledge is something to be memorized, not understood. Conventional cookbook laboratories demand little mental engagement, scant decision-making and creativity, and misrepresent the nature of science and what makes science an interesting career. Scientific knowledge becomes something to regurgitate when called to do so, not something to use and apply in any meaningful way. Science is something others do, not what students experience. The end result is training (a poor one at that), not education. Not surprisingly, these kinds of experiences, so pervasive in school science, results in students who dislike science, poorly understand science concepts, and hold significant misconceptions regarding what science is and how it works. This in turn has unfortunate ramifications for achieving STEM literacy necessary for informed socioscientific decision-making and for motivating and preparing students for STEM careers. Students and society deserve better. As several scientists have noted, if science really worked as school science implies, almost no one would become a scientist.

The next article in this series will address key features of science teaching that are crucial for achieving the goals listed in Table 1 and promoting among students the characteristics of science and scientists.



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