ABSTRACT: At the heart of theoretical and practical ideas about science education is an image of scientific work. This image draws attention to particular features of scientific work, which then guides scholarship and pedagogy in science education. In the field of science education, much discussion in this vein focuses on the question, “What is the nature of science?” Most images of science found in education, psychology, and philosophy emerge from conceptual and methodological perspectives that emphasize norms, conventions, and broad trends. Some groups are motivated to distinguish science from other activities while some groups work in the opposite direction and blur the lines between science and others ways of knowing. Underlying both perspectives is an implicit focus on general qualities common to groups or subgroups (e.g. believing that ideas are subject to change, explanations demand evidence, science is a complex social activities, etc.). I propose that the vital qualities of science are best illuminated by just the opposite process: by appreciating the uncommon, rather than common, features. By attending to individual variation, we are more likely to understand what makes science a creative, motivating, and deeply personal enterprise. In addition, appreciating these variations reveals judgment, creativity, adaptation—the hallmark of scientific work. Implications of this perspective for science education are discussed. © 2002 Wiley Periodicals, Inc. Sci Ed 86:386–400, 2002; Published online in Wiley Interscience (www.interscience.wiley.com). DOI 10.1002/sce.10023

WHY LEARN ABOUT THE NATURE OF SCIENCE?

Understanding the nature of science has long been acknowledged as an important educational outcome (Lederman, 1992). For many people, science exemplifies a rational perspective on the world and, thus, to learn science—especially its processes—is to learn to be better thinkers or problem solvers in general. Several reform efforts during the 1960s constructed entire curricula on this assumption (see Science: A Process Approach (AAAS) and Elementary Science Study (EDC) as examples). Some contemporary scholars similarly propose that student understanding of the nature of science is preparation to be problem solvers in the broadest sense, i.e. “become scientific in their approach to life’s problems” and to be participants in a democratic society (Mathews, 1994). In addition, because we live in a society saturated by developments in science and technology, an understanding of the nature of science enables students to be more informed consumers of scientific information (Lederman, 1999).

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Scholars focused on learning also see relationships between students’ understanding of the nature of science, their epistemological beliefs, and their conceptual understanding. In general, students who believe that knowledge is a dynamic human construction tend to approach learning in ways that lead to deeper conceptual understanding (Carey & Smith, 1993; Hammer, 1995; Linn, Songer, & Lewis, 1991). Gallagher (1991) and other proponents of the history of science propose that the nature of science is worth understanding in itself. To appreciate the nature of science through a historical lens is to highlight important constructivist themes such as (a) knowledge is a human construction rather than something that has always existed, (b) scientists are fallible rather than infallible, (c) scientific knowledge is constantly evolving rather than static, (d) scientists and their ideas are influenced by the technology and social and political forces of their time.

Another Reason

I propose another reason why students should understand the nature of science. In studying the nature of science, students should not simply understand epistemological beliefs and methodological procedures, but also appreciate what makes science vibrant, exciting, and fulfilling. That is, students should gain a sense of what brings life to the discipline, the community, and, most of all, individual scientists. The “nature” of science should capture that which makes it a creative, motivating, and deeply personal enterprise. In short, to study the nature of science is to appreciate its vitality. By focusing on vitality, I make a direct link to some of the central problems of K-12 science education: vitality is precisely the quality that students least experience when learning science.

TWO GENERAL APPROACHES TO DEFINING THE NATURE OF SCIENCE

The two questions—“what is the nature of science?” and “what gives science its vitality?”—seem simultaneously related and unrelated. On the one hand, the nature of any vibrant human activity must certainly be related to that which gives it vitality. On the other hand, most discussions about the nature of science somehow fail to give adequate treatment to the question of vitality. The focus on beliefs, values, procedures, and activity does not convey the inherent human drama and personal significance of scientific work. I contend that our inability to appreciate these qualities is a direct consequence of how we have traditionally approached the study of the nature of science. Two conventional approaches to defining the nature of science are described. Next, a critique of these approaches sets the stage for a third approach.

One Approach: Demarcate Science/Nonscience Boundaries

Certainly one of the earliest efforts to describe the nature of scientific work is found in Aristotle’s “Nichomachean Ethics” where he distinguishes three kinds of intelligent activity. Theoretical, practical, and productive activities are distinguished by their goals, activity, outcome, and subject of interest. For example, in theoretical activity—what we would call science—observation, inquiry, and reflection lead to timeless theory that describes laws of nature. By contrast, practical activity is more concerned with conduct in the realm of human society: taking action that can be justified as ethical and worthwhile. Production activity emphasizes making things that were functional and aesthetic (Aristotle, 1951). Many subsequent philosophers would also employ a similar approach—using broad categories demarcated from one another—when describing important qualities of human nature and
conduct. In Aristotle’s system and in many others since, the nature of science is defined by demarcating it from other intelligent activities.

Descartes contributed to the further elaboration and elevation of a scientific worldview when he highlighted the importance of rational thought as a means for developing privileged understanding of the world. A central figure in the Age of Enlightenment, Descartes argued that the power to understand, to determine truth, and to make justifiable decisions had less to do with individuals’ position within the dominant political, social, or religious order and more to do with their ability to think rationally. The power of reason, soon to become synonymous with the power of science, was defined, once again, by demarcating it from other means of persuasion.

The general tendency to distinguish science from other ways of knowing was pushed even further by Karl Popper. During Popper’s life in the first half of the twentieth century, the world saw a rise in the influence of Marx’s politics, Freud and Adler’s psychology, and astrology. Popper (1985) began his argument by noting how individuals were seduced by the seemingly limitless explanatory power of these new ideas. In response, Popper established criteria distinguishing legitimate science from pseudosciences. Taking direct aim at the central appeal of the popular “nonsciences,” he contended that a theory’s falsifiability, rather than its verifiability, qualified it as scientific. A true scientific theory generates testable predictions. If the predictions were not supported by data then the theory would be disproved; if the predictions were verified, then the theory is not verified, but simply not disproved. Other philosophers, such as Lakatos (1978) and Thagard (1988) later modified parts of Popper’s broad argument but retained the overall agenda of distinguishing science from other activities.

Thus, the method and rhetoric of demarcation has been a powerful means for identifying and representing important qualities of science. This method generates science’s common features, including an emphasis on logical reasoning, assumptions about the relationship between theory and evidence, beliefs about the nature of reality and theory, and so on. Psychological and educational perspectives often reflect general trends in philosophy and often translate epistemological perspectives into theories of learning and instruction. For example, developmental psychologist (Kuhn, 1989; Kuhn, Schaubule, & Garcia-Mila, 1992) points to the ability to coordinate theory and evidence as a distinguishing quality of scientific reasoning. Reif and Larkin (1991), cognitive psychologists from the paradigm of expert-novice research (itself a paradigm of demarcation), further contribute to a characterization of how scientific and nonscientific thinking differ. In their work, scientific and everyday reasoning are distinguished by different goals, knowledge structures, methods, and concerns about quality. Other scholars have proposed general criteria for scientific work, including careful coordination of evidence and explanation (Perkins, Faraday, & Bushley, 1991), complete, systematic testing of all factors associated with a phenomenon (Schaubule, 1990), and constant attention to consistency of ideas (Nickerson, 1991).

The large body of research on children’s understanding of scientific concepts also reflects an analytical perspective that relies on distinguishing scientific from nonscientific. Children’s ideas and explanations about natural phenomena such as motion, heat and temperature, the movement of the moon and planets, and plant growth are analyzed via a contrast with scientifically correct explanations (see Driver et al., 1994 or Osborne & Freyberg, 1985 for a summary of research in this area). To highlight the disparity with scientific ideas, children’s conceptions are labeled as “naïve” or “misconceptions.” Similarly, Carey and Smith (1993) and Linn and Songer (1993) describe children’s epistemology—beliefs about the nature and origins of scientific knowledge—by contrasting their views with more scientifically sophisticated views.
Project 2061 (Rutherford & Ahlgren, 1990) is a good example of how science education reform draws on the list of commonalities inspired by philosophical analyses. According to Project 2061, science is described by particular world views (e.g., world is knowable, ideas are subject to change), methods of inquiry (e.g., demands evidence, based on logic and imagination, is not authoritarian), and kind of enterprise (e.g., complex social activities, ethical principles). These qualities are intended to describe science at a more general and, ostensibly, more powerful level.

In sum, demarcation approaches strive to describe science as a whole and scientists as a group. In doing so, science and scientists are contrasted with nonscience and nonscientists to generate lists of general characteristics or commonalities. I next describe a different analytic approach, one that characterizes the important features of science by blurring, rather than demarcating, the boundaries of science.

A Second Approach: Blur Science/Nonscience Boundaries

In the spirit of postmodernism and postpostivism, many argue that there is nothing particularly unique or special about the method or knowledge of science. It is, therefore, unnecessary or, perhaps, harmful to distinguish science as a unique and privileged way of knowing. With roots in sociological, historical, or critical analysis of text, this approach tends to examine the nature of science by blurring, rather than demarcating, boundaries between science and other activities. For example, Feyerabend (1978) argued passionately that science is undeserving of its privileged status. He contended that there is nothing special about its method and, besides, science is not as deeply rooted in an infallible system of logic and evidence as it purports. Feyerabend goes so far as to say that the only thing that can be honestly said about the “method” of science is that “anything goes.” The nature of science, as a result, can only be defined circularly, i.e., “science is what scientists do.” Feyerabend contends that science is undeserving of its elevated status not only because it lacks any distinct method, but also because to privilege any way of knowing over others is antithetical to a free society. Thus, Feyerabend argues for equal status among all ways of knowing and goes so far as to put religion, mysticism, intuition, and science on equal footing.

Although Feyerabend’s position may seem extreme, his general wariness of any “privileged perspective” is one of the distinctive qualities of the postmodern thinking. Philosopher Hanson (1958) argued almost half a century ago that all observation is inevitably theory-laden and, therefore, no claim to objective or privileged observation is possible. In addition, social psychologists, sociologists, feminist scholars, and critical theorists have further raised our awareness that prior knowledge and experience, historical and cultural context, and power and authority influence the construction of meaning. Meaning is far from a simple logical product of observation and rational thought.

In psychology, there is also growing empirical evidence that distinctions between scientific and everyday activities are more nebulous than demarcation perspectives might suggest. For example, not only is reasoning by nonscientists and children frequently rational and systematic (Karmiloff-Smith, 1988), but reasoning by scientists is routinely informal, personal, and biased (Faust, 1984; Kuhn, 1970). Additionally, the role of nonrational or non-logical reasoning by scientists—which has always had a somewhat obscure philosophical basis—is being appreciated by psychologist as necessary to advancements in the field (Faust, 1984; Kuhn, 1970). For example, the “nonscientific” practice of continuing to support a theory or developing ad hoc theories in light of disconfirmatory evidence has often proven to be a practical and effective strategy throughout the history of science.
CRITICAL RESPONSES

How have science educators responded to these efforts to characterize the nature of science? Lederman (1995) points to the difficulty and potential pitfalls of characterizing the nature of science. He draws on Suchting’s philosophical analysis (Suchting, 1995) to suggest that the nature of science varies both across disciplines and over time. Lederman cautions that static, generic lists of process skills seriously misrepresent actual scientific practice. Duschl (1988), Duschl, Hamilton, and Grandy (1992) also highlights how methodologies in science change with technological advances and how these developments are inextricably linked with the theoretical development in a domain.

Mathews (1994) is similarly concerned about misrepresenting the nature of science and makes an important observation about what I call the “hegemony of constructivism.” Although there may be certain best views, Mathews argues that teaching the nature of science is subsumed under the broader liberal, democratic goal of teaching students to think on their own, i.e. to make justified choices. In this light, Mathew recommends that the nature of science be approached inductively and tentatively rather than didactically and assertively.

Lederman, Duschl, and Matthews raise important critiques to current approaches to understanding and teaching the nature of science. I share their concerns that current progressive science education practices may represent science too narrowly. At this point, it seems reasonable to ask, “To what degree do our current representations of the nature of science correspond with the actual practice of scientists?” For example, to what degree do the general qualities defined by AAAS (e.g. science ideas are subject to change, science demands evidence, science is a complex social activity, etc.) apply in any meaningful way to real scientists?

Glasson and Bentley (2000) provide one of the few studies that addresses the empirical question of “what is the nature of science?” rather than the philosophical/normative question of “what should the nature of science be?” Glasson and Bentley interviewed scientists from various disciplines and reported they expressed a range of viewpoints about the nature of science—a range that often lay outside what we might consider current constructivist epistemology. The fact that scientists seemed to have diverse views seems consistent with Lederman (1995) and Suchting’s (Suchting, 1995) belief that views about science vary across disciplines.

However, one might also interpret differences among scientists as inconsistent, arbitrary fluctuations that, in turn, reflect inconsistent, arbitrary beliefs on the nature of science. On this point, Feyerabend (1978) asserts that scientists spend little time considering or debating the philosophical underpinnings of their methods. According to Feyerabend, scientists are eminently practical in their approach and largely uninterested in questions such as “what is science?”

After reading Glasson and Bentley’s report, I was moved to contact them to ask if these scientists seemed to have actually thought much about the nature of science before they were interviewed. Bentley and Glasson replied

… although they were very willing to speak about the nature of science in their work, they had not pondered this topic prior to the interview. (Glasson 03/2001, personal communication)

In my opinion, not much thought if any had been given to it (nature of science), or at least for a very long time. My impression was that the epistemological question had either never occurred to them, or had been settled in their mind so long ago that it was now just a given, an unconscious, unquestioned background frame of reference. I think that one aspect of the reason why is that the epistemology of science is something more salient to philosophers than to scientists … (Bentley, 03/2001, personal communication)
Glasson and Bentley’s observations should prompt educators to carefully reconsider why students need to understand the nature of science when scientists themselves do not seem to think much about it. Similarly, if students are to learn about the nature of science, they should appreciate qualities that are distinctive and salient to the experience of scientists.

What qualities of science then might be salient to scientists? Rather than general beliefs about epistemology and practice, perhaps the vibrant qualities of science have more to do with the drama of inquiry, the delight of discovery and insight, or the pride of accomplishment? An educationally worthwhile conception of the nature of science should capture the vitality of science, i.e. that which makes science engaging, worth doing, and personally meaningful for scientists. In the next section, I discuss how approaches that demarcate or blur the boundaries between science and other activities are inherently ill-suited to adequately represent the vitality of science. An alternative approach is introduced that enables us to better appreciate these qualities.

AN ALTERNATIVE APPROACH: APPRECIATE INDIVIDUAL VARIATION WITHIN SCIENCE

Although the “demarcation” and “blurring” perspectives differ in important ways, both draw our attention to commonalities rather than variations and tend to describe groups rather than individuals. This tendency toward the general leaves unexamined much of what gives science its vitality. Let’s return to the starting point of this essay. I am concerned about science education and begin—as many others have—with the question, “what is the nature of science?” Unlike others, I choose to define the “nature” of science as that which gives it vitality. I define vitality as the degree that scientists are made more alive, more human by their work. This rather peculiar notion of the nature of science makes more sense if one can see the problem of education as a lack of vitality in students as they learn science. The absence of vitality is manifest in their boredom, indifference, and disenfranchisement. Thus, in order to understand how students might come alive with science, we must first understand how this happens for scientists.

To what degree do perspectives that either demarcate or blur boundaries between science and nonscience capture that which makes science vital and alive? Similarly, to what degree do these perspectives lead to science teaching that makes science vital and alive for students? Granted, recent reform has encouraged educators to attend to students’ conceptual understanding, epistemological beliefs, reasoning strategies, goals, or the sociological features of the classroom. Like scientists, students are prompted to believe that knowledge is a dynamic human construction, articulate and coordinate theory and evidence, and participate in a community of inquiry (Carey & Smith, 1993; Linn & Songer, 1993; Schauble, 1990).

Evidence from classroom-based research is promising and I leave further judgment to individual readers. My point in this paper is that there are important qualities of science, particularly qualities central to its vitality, that both perspectives are inherently ill-prepared to illuminate. The analytic approach of these seemingly different perspectives share two related characteristics: (a) a focus on the boundary (or lack of it) between science and nonscience, and, consequently, (b) a tendency to describe group commonalities.

To identify science’s common qualities is to tell only half of a good story. To truly understand the nature of science—or anything for that matter—is to understand qualities unique to individual scientists as well as qualities common to all scientists. Therefore, I recommend a third, complementary analytic approach that (a) focuses on “boundaries” (i.e. distinctions) between individuals within science, rather than between science and nonscience, and, consequently, (b) describes variation, rather than commonalities, within science. The
conventional attention to norms or commonalities tends to maximize differences between groups, while minimizing within group variation. Common qualities purported to apply to everyone in general can sometimes apply to no one in particular. Important differences and nuances within the vast domain of scientific practice itself are often overlooked (see Raizen & Michelsohn, 1994, pp. 61–62, for a few examples of the variety of scientific reasoning).

Commonalities describe only the outline, not the substance, of the picture of science. The universe of scientific work—across disciplines, in a variety of intellectual, political, and institutional contexts, and across many different individuals—ends up seeming rather dull and homogenous. Vitality lies in the details and variations within the broad outline. Exceptions to the norms of actual practice of scientists are far from being “noise in the data”—instead, they are signs of individuality, originality, and creativity. Oliver Sacks, a neurologist and writer, provides a vivid example of how an appreciation of individual variation within science can illuminate its vitality. Before discussing the broader features of this approach to understanding the vitality of science, we begin with an example from Sacks.

**An Example: Oliver Sacks Portrays Temple Grandin**

In *An Anthropologist from Mars*, Sacks (1995) introduces us to Temple Grandin, an autistic adult. We learn about general clinical symptoms of autism such as impaired movement, social interactions, and verbal and nonverbal communication. During his extended visit with Ms. Grandin, Sacks observes that she shows signs of all of these impairments. In particular, her autism makes it difficult for her to understand, relate, and connect to the experiences of others. Despite her condition, Ms. Grandin’s days are not spent idle in a special care facility. Instead, she is a world-renowned animal scientist at the University of Colorado. Sacks takes us beyond immediate appearances and helps us appreciate how Dr. Grandin’s life as an individual and her life as a scientist are connected in ways that are profound and vital.

Despite her inability to connect to other individuals, Sacks learns that Temple is nonetheless immensely comforted by physical contact. Unfortunately, because of her autism, being touched by another person is both overwhelming and soothing. Sacks discovers that Temple has built a large V-shaped trough in her house. Everyday, she lies down in her “squeeze machine” and via a system of pressure hoses is able to make the padded sides of the trough press in on her firmly, but gently. Temple demonstrates her machine for Sacks and he observes that this process indeed has a dramatic calming effect on her speech and behavior.

While autism makes it difficult for Temple to connect to other people, she is remarkably sensitive to the experiences of the animals she works with. In fact, she has dedicated herself to comforting livestock as much as possible in their times of suffering. As Sacks is given a tour of the university livestock facilities, he comes to a system of corrals and chutes used to herd animals toward whatever “procedure” awaits them. Here he sees something that Temple has designed and this encounter becomes the dramatic highpoint of his story. As the animals move along in single file, they become highly confused and distressed. Just as they reach their final destination, the animals enter a section of corridor where the side walls move inward to gently and firmly squeeze and calm them, one by one.

Sacks has flair for finding the unexpected, the variation from the norm. This is not simply a dramatic rhetorical technique, but central to his view of how individuals are to be understood. Although he brings an enormous wealth of clinical knowledge, his analysis is not an effort to classify the individual as being a case of a particular medical condition. Through a thoughtful appreciation of that particular individual comes insights to the broader domains such as the experience of autism, what it means to be human, and the nature of science. To delineate how Temple Grandin’s work is or is not scientific—to emphasize only general qualities that apply to all members of a category—seems to be less satisfying and
less enlightening than to appreciate what make this special individual unique, vital, and, ultimately, effective in her work.

APPRECIATING INDIVIDUAL VARIATION AS RESEARCH METHOD

Oliver Sacks has an expert understanding of neurology and psychology. He is certainly able to quickly recognize qualities in Temple Grandin as characteristic of broader descriptive categories, such as autism. Fortunately, Sacks is patient, attentive, and open-minded. He spends time with Temple, enabling his initial impressions to expand, deepen, and change. By appreciating how she varies from preexisting categories and group commonalities, he begins to see her as an individual, the intimate expression of herself in her science, and, most importantly, as a vital human being.

Sack’s approach to understanding Temple Grandin and, concurrently, the nature of her science is grounded in a certain set of purposes, assumptions, and methods of inquiry. His ability to appreciate individual variation is more than simple technique—it is well developed methodology. Eisner’s image of the social scientist as a “connoisseur” comes to mind:

The ability to make fine-grained discriminations among complex and subtle qualities is an instance of what I have called connoisseurship. Connoisseurship is the act of appreciation. (Eisner, 1998, p. 63)

Eisner refers to critics of art, food, and wine to illustrate how connoisseurship is perception informed by deep knowledge of the subject. The skill of connoisseurs is their ability to be aware of qualities—specifically qualities that matter—and to understand their significance. Furthermore, connoisseurs, also known as critics, facilitate the perception of others. Although our preconception of connoisseurs and critics may conjure images of snobbish show-offs, one of their central roles is as teachers who help others attain greater depth and significance in their experiences.

The “method” of appreciation is central to seeing science’s vitality. By appreciation, I rely on a particular, perhaps uncommon, definition of the term. In its common use, to appreciate is to grasp, enjoy, or value something. These definitions are useful but incomplete. Consider, by contrast, Dewey’s notion of appreciation (Dewey, 1916):

In one of its meanings, appreciation is opposed to depreciation. It denotes an enlarged, an intensified prizing, not merely a prizing, much less—like depreciation—a lowered and degraded prizing. This enhancement of the qualities which make any ordinary experience appealing, appropriate—capable of full assimilation—and enjoyable, constitutes the prime function of literature, music, drawing, painting, etc., in education. (p. 246)

Thus, appreciation takes time and is, consequently, an event rather than a steady state. Rather than to grasp, enjoy, or value, to appreciate is the process of grasping more fully, enjoying more profoundly, or valuing more deeply. Drawing on Dewey’s theory of aesthetics (Dewey, 1934), Jackson (1998) elaborates the activity of appreciation using the example of art:

The true appreciator of an art object, for Dewey, is not the casual listener or viewer. Rather, he is someone who has spent time with a work, has found it engaging, stimulating, puzzling, perhaps even troubling, and, as a result of his sustained exploration of it, has undergone a significant change of some kind. His encounter with the object or performance forces him to modify his former habits, his old ways of looking at things. The new and the old become integrated. They form a new pattern, a new way of perceiving. (p. 51)
Given this definition of appreciation, the image of the connoisseur may be somewhat misleading. Appreciation by connoisseur or critic is sometimes imagined as being able to stand in front of a painting and carrying on in a confident display of understanding. Although drawing upon funded understanding of this kind—Eisner (1998) calls this antecedent knowledge—is important, it is not appreciation. True appreciation, according to Dewey and Eisner (who is also a Deweyan scholar), is to see a work of art with fresh eyes, no matter how many times it has been viewed before. Thus, perception draws less on the ability to identify and process information quickly—typical attributes of intelligent performance—and more on the ability to be inspired by ideas, to act on this inspiration, and to be moved or transformed by the consequences.

To appreciate, then, is to allow oneself to be open to it, to be moved or swept away in an experience. Sacks’ story of Grandin and many other stories require that he live in their world and to experience the world “as if” he were them (see also “The Island of the Colorblind and Cycad Island” where Sacks spends several months living among people he wishes to understand). The heart of appreciation—the emergence of perception from recognition—is a complex process. Appreciation requires both skepticism and openness to new ideas and experiences, both an objective perspective and a willingness to suspend disbelief, and both well-developed metacognition and a genuine “un-self-consciousness.” On the one hand, the connoisseur must be logical, careful, and conservative. On the other, like a work of art, the meaning of individual variation cannot be fully experienced unless we get inside the lived experience of the scientist—to experience and make sense of the world as they do. Managing these tensions is difficult, but is essential to the art of appreciation.

APPRECIATING THE VITALITY OF SCIENCE: ANOTHER EXAMPLE

Sack’s story helps us appreciate the interconnection between Temple Grandin’s personal characteristics and the substance of her scientific work. The idea that animals need comfort in the jarring, traumatic environment of livestock corrals and the means by which she proposes to comfort them is vividly connected to her own history and way of experiencing the world. We see how her science is a profound expression of who she is and who she wishes to be. The next example illustrates how individuality is expressed not only in the ideas of scientific work but also in the way of scientific work.

Bill is a professor at my university doing work in the physics, psychology, and physiology of acoustics. He is a friend of mine—we play in the same tennis league—and this relationship between us helps a great deal in my doing this kind of research. The interconnection between individuals and their work, i.e. what makes their work uniquely “theirs,” is often private territory and is not easily explored. A certain level of familiarity and trust is prerequisite. When I interviewed him, one general strategy employed was to get Bill to describe how his work was different from others. Also, I encouraged him to consider directly how his work was meaningful to him in a deeply personal sense. Here are some things I learned.

Bill describes himself as extremely sensitive to sound. As it turns out, Bill was practically blind for the several months as a young boy. During this period of temporary blindness, he had to depend heavily on his sense of hearing. Presently, he is aware of many sounds that others may not notice. Furthermore, sounds evoke an unusually strong reaction as he finds many sounds extremely pleasing or irritating. His life’s work has been the study of sound and its perception. In his laboratory sits a large anechoic chamber used for the careful study of how we perceive sounds. The parallels between his scientific work and his own personal lived experiences are unmistakable.

As I looked around his lab, Bill was eager to point out that he had built most of the electronic equipment himself. He pointed out that most scientists would not dedicate their time
and energy to such a task—instead, they would just order the equipment right from the manufacturer. I suggested that he must have always been good at building things. As it turned out, the situation was exactly the opposite. As a young student, Bill was not at all competent at building things. However, Bill has a persistent, almost dogged, determination to improve in areas that he is not adept. I see this quality also in his tennis: although he does not possess as much natural ability as some other players, he practices longer, harder, and more seriously than anyone else. For Bill, science is an opportunity to overcome, to become better. The beautiful equipment in his lab is a testament to this desire and is displayed with obvious pride.

The themes underlying Bill’s interest in acoustics and his love for building equipment illustrate how his work is a manifestation of who he is as a person—pointing simultaneously from whence he came and to where he might like to be. Appreciation of variation illuminates science as the work of individuals, each with a deeply human and compelling story that plays itself out in their work.

**IMPLICATIONS FOR THE STUDY OF SCIENCE: VARIATION AND INVENTION**

The philosophical treatment of science often analyzes it into two components: the generation of ideas and the evaluation of ideas. The vast majority of psychological and philosophical work has been concerned with the latter process and has examined how the value of knowledge claims such as deductions, inferences, and theories, can be assessed. In the rationalist tradition, claims to knowledge are typically based on appeals to logical conventions and empirical substantiation. Those who tend not ascribe to such logical or empiricists perspectives turn to social and community forces as arbiters of privileged knowledge.

In contrast the question of how original ideas come about—ideas that are then subsequently evaluated—has received relatively little attention. Popper called for bold conjectures, yet chose not to elaborate on where new theories and bold conjectures came from. Scholars spanning from Plato to contemporary constructivists acknowledge the problem of invention: if observations, problems, and solutions are all grounded in what we already know about the world, how is it rationally possible for truly new knowledge to develop? Is it not true that we can only see the world in terms of what we already know? While it is clear that new ideas do, indeed, emerge, the means by which they come about remains rather opaque. Rorty went so far as to say that the whole creative process was beyond the realm of philosophy and seemed to resign it to the realm of the mystical (Rorty, 1989).

Rorty’s cynicism aside, there has been some progress made on understanding the invention of ideas. In fact, Rorty’s predecessor in pragmatism, Peirce (1931–1958), proposed the metaphoric process of abduction—a borrowing of old ideas from other areas to create new ideas—as central to the development of scientific understanding. Other philosophers such as Hesse (1966), Ortony (1979), and Petrie (1979) have also written about the role of metaphor in science. In addition, psychological research has begun to build a promising empirical basis for how metaphorical and analogical reasoning can function in the generation of new ideas (Schon, 1979; Vosniadou, 1989; Wong, 1993a, 19993b).

In both philosophy and psychology, the study of invention has, for the most part, been removed from the practice of actual scientists. Theories of invention or creativity have largely abstract and theoretical origins—for example, the logic and design of artificial intelligence systems has had more influence on theories of creativity than observations of practicing scientists. This state of affairs leads us back to, what should by now be, a familiar theme.
The study of the nature of scientific practice tends to look for the abstract, the general, the common. While these broad descriptions are useful, it is not difficult to see how an exclusive focus on commonalities is unlikely to account for acts of invention; invention, at its core, is a distinct departure from convention, norms, and standards. These variations can only be appreciated by focusing on and understanding scientists as individuals and what makes science their science.

For example, where did Darwin come up with the idea of origin of species? Some accounts would have us believe that it emerged via a process of induction from his observations as a naturalist. Or, might it also be important to consider that one of Darwin’s good acquaintances was a dog breeder? Perhaps, Darwin’s general ideas about the origin of all species emerged via Peircean abduction from his knowledge of how dogs can be bred to have or not have particular characteristics. Similarly, Barbara McLintock’s work as a Nobel prize winning cytogeneticist is more fully appreciated when we understand the interconnection between who she was as a person, her unique approach to understanding plants, and the radically new ideas about plant genetics. A simple chronological description of her accomplishments—so typical of how famous scientists are represented—cannot adequately account for the unique nature of “her science.”

**IMPLICATIONS FOR SCIENCE EDUCATION**

The vitality of science is the dynamic relating of individuals’ lives, their work, and their ideas. Scientists are made more alive and more “fully human” in their science as they experience a greater capacity for action, feeling, and thought. To do science is to be inspired—a word derived from the Latin *spirare* meaning “to breath.” To inspire is, literally, to breathe life into something. The goal of education is for science students to appreciate this vitality and to be similarly inspired. How might this be accomplished?

Returning to the portrait of Temple Grandin, we can learn from Sack’s skillful use of stories to both develop for himself and foster in others appreciation for the subject. As a research method, Sacks tries to understand what makes Temple a unique human being by attending to her words, actions, and interactions with others in much the same way as one attends to the development of characters in a play (see also Bruner’s discussion of narrative ways of knowing, Bruner, 1985). Sacks uses the rhetoric of story to gain insight into the dynamic integrity of autism, science, and individuality that is Temple Grandin. Thus, to create and participate in a story is a means by which we might understand what it is like to be someone other than who we are.

As a researcher, Sacks strives not only to get insight to the experience of the subject, but also to accurately and effectively represent that experience to others. As a method for representation, a story moves its audience by drawing them into a particular kind of experience. The epistemological assumption underlying the rhetoric of story is that world of Temple Grandin can only be understood by seeing with her eyes, by feeling her emotions, by interacting with others as she does, and so on. In other words, the vitality of science can only be appreciated by actually experiencing it for oneself. Artfully rendered stories, as used by Sacks and others, offer one possibility for developing students’ appreciation for the vitality of science.

The task of the teacher is help students experience the stories of individual scientists “as if” they were that scientist and not outside observers looking upon the scientist. The challenge of the teacher is to get students to enter the realm of the possible and to live, if only for a while, “as if.” Thus, a story has to be rendered in a way that evokes, rather than denotes, the vitality of science.
In order for students to be moved by the scientists’ stories, teachers must be able to skillfully develop scientists as characters. On the one hand, they must be believable. Characters are believable to the degree that they respond to situations in ways that we recognize: perhaps identifying with, perhaps not, yet always falling within the range of the possible. However, if a character were entirely or merely familiar, they would not be truly compelling. Paradoxically, they would not be believable for no person is merely familiar. There must also be something individual or unique about the character. The character that we “care about” is one who is not simply a stereotype, a mere sum of the qualities common to others who have played the general role of hero, villain, victim, and so forth. The unique details and nuances that are the substance of personality and style engage us. Thus, the importance of individual variation. In addition, the most interesting characters are not only those who begin as compelling individuals, but also those who become compelling as they change or evolve in the course of events. For both the characters and their audience, transformation is essential for vitality. Therefore, just as scientists are transformed in their work, students can be similarly transformed in their appreciation of scientists’ stories.

What Science is “Learned” in Appreciation?

In Dewey’s theory of aesthetics (Dewey, 1934), which undergirds much of this discussion, the vitality of the experience of appreciation is not simply general effusiveness about something, but energy and feeling about particular, substantive ideas. Therefore, these instructional activities should not be confused with those classroom activities that rely on superficial stimulation that is relatively devoid of subject-matter substance to “engage” students.

What, then, of substance might be learned from stories like Sack’s portrait of Temple Grandin? To begin, students can appreciate that science is an expression of creativity and individuality and that scientists are made more vital in their work. Through science, individuals form not only new ideas but also themselves. Therefore, individuals become scientists, rather than are born scientists. In addition, science thrives on individuality—there is not a typical “science person.” Appreciating individual variation, then, militates against the pernicious assumption that one is either a science person or not. Furthermore, students can appreciate how the nature of science—as an act of individual expression—is also flexible. Scientists, particularly vital individuals like Temple Grandin, do “their science” not just some general or preestablished science.

In addition to painting a portrait of a unique individual, every story also embodies particular scientific ideas. In Temple’s story, a core subject matter idea is that creatures of all kinds have a deep, innate need for touch. In a biology or psychology course, Temple’s story could easily connect to Harlow’s famous experiments with mother monkeys and their offspring. Furthermore, ideas about the innate need for touch can also relate easily to students’ own experiences and intuitions about human nature.

Finally science’s vitality should be portrayed in ways not only illustrative but evocative. Returning to Dewey’s language, students should not only recognize the living connection between person and idea, but they should also perceive or appreciate this connection. Effective teaching through stories or other means requires that students learn by experiencing a vitality similar to scientists’. Therefore, to appreciate vitality of science is to enter a different kind of experience and to be more alive in it. For example, students who appreciate the role of individuality in science could begin to see beyond the stereotypical images of scientists to see the human, perhaps all too human, person at its core. Or perhaps, Temple’s story inspires them to view their own potential as scientists in a different light. Students can also be caught up by the idea that touch is a basic need. As part of their experience with
this idea, they may begin to develop new insights and feelings about their own life. They may even be inspired to act differently as a giver or receiver of touch. These hypothetical examples illustrate that the goal of appreciation is for students to become more vital by inspiring new thoughts, feelings, and actions.

CONCLUSION

What is the nature of science and, in particular, what about it is worth teaching to students? I have suggested that most images of science found in education, psychology, and philosophy emerge from a conceptual and methodological framework that emphasize norms, convention, and broad trends. It is assumed that the essence of science is its common denominators, those qualities or commonalities shared by scientists as a group. Individual differences are seen as little more than innocuous or distracting personality: something akin to statistical “error variance.” In this paper, I have suggested that omitting variation, nuance, and detail leaves little more than outlines and bare canvas in our portrait of science. The vital qualities of any kind of complex, creative human endeavor may be best illuminated by just the opposite process: by appreciating the uncommon, rather than common, features. Individual variation reveals judgment, creativity, adaptation—the hallmark of scientific work. Acts of insight and inspiration are all notable as departures from, rather than conformity to, a “standard practice.” Similarly, pushing beyond commonalities to qualities that make each individual unique, complex, and dynamic—seeing discrete individuals, not just a homogenous group—is essential to appreciating how science as fundamentally human and vital.

REFERENCES


