Chapter 6

Exchanging the Myth of a Step-by-Step Scientific Method for a More Authentic Description of Inquiry in Practice

Rebecca Reiff-Cox

The National Science Education Standards (NSES) describes scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work" (NRC 1996, p. 23). This emphasis on diverse ways is infrequently depicted in science textbooks which tend to emphasize a single scientific method to describe scientific inquiries (Anderson 2002; Sterner 1998; Bauer 1992; Conant 1947). One of the most prevalent myths about science is scientists use a single method to solve problems (Lederman 1998; McComas 1996; Bauer 1992; Duschl 1990; Conant 1947). There is some utility in discussing the single scientific method to identify the steps and characteristics of scientific investigations but this one-size-fit all model does not accurately reflect the diverse approaches that real-world scientists take when conducting investigations. This chapter will focus on the myth and reality of the scientific method so that science teachers can better provide students with accurate views on how scientists contribute to the scientific knowledge base. Before discussing the reality of the scientific method, it will be useful to examine how textbooks often portray knowledge production in science.

6.1 The Myth and Reality of the Scientific Method

The traditional step-by-step scientific method often included in textbooks as the school science version of scientific inquiry typically lists the following steps: (1) recognition of a problem, (2) collection of relevant data, (3) formulation of hypoth-

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R. Reiff-Cox (✉)
Hollins University, Roanoke, VA, USA
e-mail: rcox@hollins.edu

W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_6

eses, (4) testing of hypothesis, and (5) drawing conclusions (Dressel et al. 1960). Certainly these events or steps do occur as scientists generate knowledge, but as Cooper 2002; Lederman 1998; McComas 1996; and many others have pointed out, a stepwise model for inquiry is not reflective of how real science is conducted and using this model, therefore, fails to portray accurately the lively and diverse processes scientists use in approaching their investigations.

The scientific method is not a recipe with measurements to take and procedures to follow (Sterner 1998; Bauer 1992; NSSE 1960; Conant 1947). Scientists' descriptions of their research processes (Cooper 2002; Gibbs and Lawson 1992; Bauer 1992; Holton 1988; Keller 1983; Feyerabend 1975; Bridgman 1955; Beveridge 1957; Conant 1947) coincide with the statement from *Science for All Americans:* "There is simply no fixed set of steps that scientists follow, no one path that leads them unerringly to scientific knowledge. There are, however, certain features of science that give its distinctive character as a mode of inquiry" (AAAS 1990, p. 4).

Therefore, a contradiction exists between the private practices of science and those portrayed to the public. So infused is the public version of science in the current culture that textbooks typically just present the stepwise scientific method as the single arbiter of progress. Most scientists know the structure of an investigation is not so sequential and rigid (Ziman 1984). However, the public is not exposed to the "months of tortuous, wasteful effort [that] may be hidden behind a few elegant paragraphs, with the sequence of presented development running directly opposite to the actual chronology, to the confusion of the students and historians alike" (Holton 1988, p. 406). Typically the format of scientific papers is prescribed and results appear to flow neatly out of the procedures, closely resembling established principles of the scientific method (Medawar 1963; Beveridge 1957).

Even though this one-sided portrayal of science as a collection of products is sharply criticized by scientists (Holton 1988; Schwab 1962; Conant 1947), textbooks and even scientific articles themselves do not often reveal the actual paths to discovery (Duschl 1985, 1990; Schwab 1962). In reality, practicing scientists use a variety of pathways to approach a problem, formulate hypotheses, or make relationships in the data (Roberts 1989; McClintock and Keller 1983; Goodfield 1981; Brush 1974, 1976; Holton 1964, 1988; Beveridge 1957; Bridgman 1955; Conant 1947).

Physicist Gerald Holton (1988) describes the science-in-the-making approach characterized by circuitous paths, unexpected findings, and false starts as private science or the *context of discovery* side of science. During the context of discovery scientific attributes of creativity, curiosity, intuition, and subjectivity are valued in selecting problems of study, framing investigations, and studying relationships in the data (Medawar 1963). This context of discovery is an essential component of science but is usually kept *private*.

In order to understand progress in science, the elements of discovery just mentioned must be included, but school science often shows only public science or the *context of justification* as typified by concepts that have been scrutinized or "dry-cleaned" to wash out signs of intellectual struggle (Holton 1988, p. 9). Textbooks reflect this public science by including the scientific method as the sterilized version of scientific progress. Hence, the public is more familiar with the context of the justification side of science whereas the context of discovery side has been neglected, forgotten, and devalued, as evident by its scarcity in science textbooks (Bauer 1992; Gibbs and Lawson 1992; Brush 1976; Medawar 1963).

The cornerstone of this inquiry process is built on the context of discovery and justification. During the context of discovery phase, scientists use their intuition, imagination, and creativity to gather information, generate ideas, connect knowledge, and frame investigations. At the frontier, scientists do not follow a linear paved road leading to the finish line. Scientists vary in the paths they take to explore their inquiries but they keep track of their journey, recording unexpected findings, landmarks, and ideas.

At the frontier of science, the scientist stands between the known and the unknown and may not have a clear direction of where to proceed or what to look for but the scientist maintains persistence and an open mind when exploring new terrain. In this context of discovery phase, scientists may see new patterns, take time to reflect on the data, try out different approaches, ask many questions, or use one's experience to relate to new findings. At this stage, the scientist may be unclear of the interacting agents, the cause of the phenomenon, or if any relationship exists (Goodfield 1981). The scientist is not attached to a particular hypothesis but is open to contradictory results, new discoveries, or the possibility of starting on a new course. Giving students the chance to explore materials and ideas has been well documented (Bybee 1997; Hawkins 1965) but explicit instruction should also include instances where scientists from all disciplines have used exploratory processes to advance the scientific knowledge base.

The need becomes to recognize the limitations of current representations of the scientific method and to generate a fluid, more dynamic model for capturing the creative, private, and messy side of science.

6.2 The Inquiry Wheel: An Alternative Description of the Stepwise Scientific Method

In an attempt to bring research science faculty into discussions about scientific inquiry, science educators Reiff et al. (2002) interviewed 52 scientists from biology, environmental science, chemistry, medical sciences, physics, and geology about their conceptions of scientific inquiry. Questions included how these scientists approach and conduct scientific investigations, what the stages are of a typical scientific inquiry, and what characteristics are seen when scientists engage in inquiry. Results of these interviews resulted in the development of a theoretical model called the "inquiry wheel" to portray more accurately scientists' conceptions of scientific inquiry and their journeys (Reiff 2004, see Fig. 6.1).

The inquiry wheel does not attempt to represent the viewpoint of each scientist nor from the perspective of a particular discipline but instead is a model built from

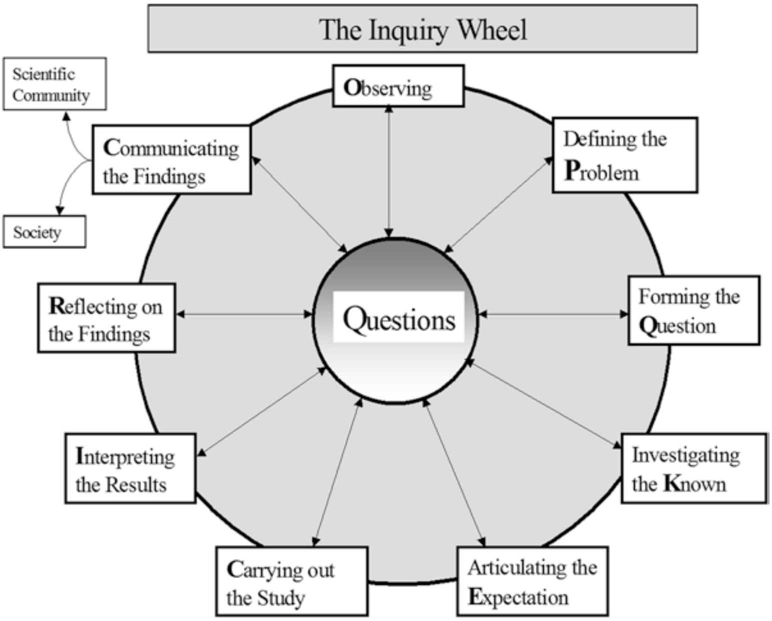

Fig. 6.1 The inquiry wheel: a model to show diverse pathways in science

the collection of scientists' responses. Each stage of the inquiry wheel is based on scientists mentioning important components of scientific inquiries. Though no science faculty member mentioned every stage and the frequency of use of each stage mentioned varied, each stage enhances the overall larger conception of interviewed scientists' conceptions of scientific inquiry (Reiff 2004).

The viewpoint of inquiry shown by the wheel contrasts sharply with the static and linear presentation of the scientific method found in modern science textbooks. The inquiry wheel is a dynamic representation of scientific processes, which continues as long as questions both large and small continue to fuel the investigation. Unlike the stepwise method, this model clearly shows the reality of many pathways to answering a question. Scientists—even the same scientist—may not follow the exact path for every investigation. Scientists "must understand science as a continuing process of inquiry, not as a set of firm answers to particular questions" (NSSE 1960, p. 31). The stages interviewed scientists shared and the descriptions of these processes were used to construct the inquiry wheel.

In this investigation of scientists' conceptions of scientific inquiry, Reiff (2004) found scientists most commonly mentioned "questions" (83%) as an essential stage of an inquiry investigation.

A geographer from this research described the central role of questions as:

> You should question everything. Question, question, question. Why, why, why? If nothing else, science is important for that. It keeps everybody on their toes. If there were more scientists, we would be on our toes. We are not on our toes.

Another frequently cited element in the inquiry process is the importance of "reflection" (61.3%). This finding corresponds to the significance of reflection mentioned by Roberts 1989; Beveridge 1957; Einstein 1944; Zinsser 1940, but does not correlate to discussions of inquiry in science textbooks. Out of 40 science textbooks surveyed, only two included reflection as part of an inquiry investigation in either text or in figures of the scientific method (Reiff 2003).

The inquiry wheel expands on the traditionally defined steps of the traditional scientific method by including stages in an investigation not commonly depicted in science textbooks. The wheel should not be seen as a cycle with one stage leading directly into another stage but is an iterative process where the investigation can begin at any stage and stages can be repeated depending on outcomes in the investigation. This fluid approach is indicated by double-headed arrows on the figure and better portrays how science is actually practiced in contrast to the standard "checklist" often found in textbooks. In the inquiry wheel model, scientists generate questions along each stage and revisit previous stages whenever needed. These questions and their answers are the force necessary to turn the wheel for an investigation to proceed.

Some research scientists interviewed (Reiff 2004) had strong opinions about how the scientific method is portrayed not only in textbooks but also in the classroom. One biologist critiqued the scientific method by saying: "The thing that happens in high school is they try to force everyone to turn their science project into the scientific method with a hypothesis and a prediction. It's absolute gibberish. It doesn't work that way." Other scientists described the process of repeating stages as an important part of the process of scientific inquiry. An anthropologist explains the nonlinearity of scientific inquiry:

> Now will they always follow along a scientific protocol or step-by-step methodology? I don't think so but then science doesn't either. Hypothesis, methodology, testing results, conclusion. Things don't move around in quite that progression; things get bumped around a bit and, I think, in everyday life I think it's the same way. You run into problems and questions and then can use science.

Consistent with scientists' descriptions of their scientific endeavors in the literature, science does not proceed in a step-by-step format with each step checked off before proceeding to the next step (Conant 1947). Science is often presented as a product (Lederman 2003) not as a process of discovery, of failures, or of persistence. Biologist, Judith Ramalay, describes the scientific process:

> People who think science is a product rather than a messy process of inquiry can become profoundly uncomfortable when they are brought face to face with the uncertainties and arguments at the frontiers of science (2003, p. 228).

The inquiry wheel does not restrict investigations to a single method using the experimental approach; the use of the phrase *carrying out the study* broadly includes multiple pathways and approaches to scientific inquiries. Science textbooks and typical science competitions commonly present the experimental approach as the only one version of scientific methodology (Cooper 2002; Lederman 1998; Gibbs and Lawson 1992; Brush 1974). In reality, scientists use a plurality of approaches that include descriptive, exploratory, correlational, experimental, or some combination of methods (Cooper 2002; Sterner 1998; Bybee 1997; Bauer 1992; Keller 1983; Goodfield 1981; Holton 1964; Glass 1967; Beveridge 1957; Conant 1947). Other stages on the inquiry wheel such as observing, communicating, reflecting, and interpreting are represented equally with carrying out the study to denote the significance of scientists spending an equal or greater amount of time on these other stages of an investigation.

The inquiry wheel provides the flexibility in that it shows scientists can begin an investigation anywhere along the overall continuum. In fact, the scientists interviewed mentioned many of these shared stages with varying starting points for investigations (Reiff 2004). Most geologists described observation as the first step in an investigation but for others, questions were the instigator of investigations. Communication occurs throughout a study in both formal and informal ways. The inquiry wheel shows the dynamic nature of scientists beginning at various stages, repeating steps, and generating questions during an investigation.

6.3 Teaching Authentic Scientific Inquiry

"Understanding [authentic] scientific inquiry can change patterns of teaching behaviors and activities in ways that are more significant and enduring than merely supplying teachers with new activities" (Bybee 1997, p. 203). As has been pointed out, too often in science classrooms, students skip the process of an investigation and are primarily concerned with the product. When students are given opportunities to engage in the process of science they do so guided by a step-by-step method that is little more than a shadow of authentic inquiry. Therefore, real science involves students understanding that not all investigations are experimentally driven nor are they mediated by a standard set of steps. The traditional scientific method list of steps should be placed within the larger context of scientific discoveries, creative approaches, and unexplored questions. This section will discuss the use of the inquiry wheel in instruction and will provide brief sketches of ways that may guide scientific inquiry.

6.3.1 The Inquiry Wheel

The Inquiry Wheel is a more accurate description of scientific inquiry generated from interviews with working research scientists and can be used as a framework to help students see science authentically as both nonlinear and multidimensional (Reiff 2004). At the lower grades, students can begin with basic components of an inquiry investigation—asking questions, making observations, and communicating with peers—and then expand on skills such as making connections in the data, selecting tools, techniques, and methods, investigating known information, and reflecting on the findings in upper grades. Instruction should move beyond the basic level of making observations and classifying.

The inquiry wheel can also be used to enhance understandings of the nature of science (NOS) by portraying a more accurate depiction of science as a dynamic and highly evolving endeavor. With questions at the center and chances to move freely about the wheel, students take an active role in participating in science learning. The static, linear depiction of the traditional scientific method does not reflect the role of questions in shifting the scientific knowledge base. Science educators can compare conceptions of the NOS before and after the use of this new model in inquiry investigations. Do students who use the inquiry wheel have improved understandings of the NOS than those using the traditional scientific method? Science educators can determine if the combined use of explicit instruction (reflection and discussions) with more implicit instruction (the inquiry wheel) can improve understandings of the NOS.

The following paths for *carrying out the study* in the inquiry wheel portray the diverse ways science advances through serendipitous moments, thought experiments, and varying research strategies (descriptive, exploratory, correlational, experimental, or a combination). The applicability of utilizing multiple approaches to carrying out scientific investigations further explicates the nature of science (NOS).

6.3.2 The Role of Serendipity in Science

Though scientists can and do plan the framework for investigations, they also value unplanned connections occurring through serendipitous moments (Roberts 1989). New theories can be conceived from a flash of inspiration, an accidental observation, a functional need, strange coincidences, or even clumsiness. Most scientists do not consider that serendipitous moments diminish the merit of discoveries (Keller 1983). The role played by chance in discovery is seldom recognized, understood, or appreciated as pointed out by Beveridge 1957, p. 32 who states, "Books written on the scientific method have omitted the reference to chance in discovery." Serendipitous moments do not happen unless the observer is receptive to thinking in different ways and places. The scientist who possesses thorough knowledge of the subject matter and who does not dismiss conflicting, seemingly trivial, and annoying results will be more likely to experience these unexpected moments. Louis Pasteur perceptively explains this readiness with his famous quip, "Chance favors the prepared mind" (quoted in Roberts 1989, p. 244).

Beveridge (1957) defines these serendipitous moments as "a sudden enlightenment or comprehension of a situation, a clarifying idea which springs into the consciousness, often, though not necessarily, when one is not consciously thinking of that subject" (p. 68). Messages from the subconscious cannot be retrieved if the mind is occupied with thoughts, worries, or is fatigued. The more passionate a scientist is about a problem the more likely ideas will break through to the conscious.

This process usually occurs after much deliberation—conscious and unconscious. Famous ideas have come to scientists (Einstein, Descartes, Wallace, and Cannon) while they were sick in bed, lying in bed, or just awakening when the consciousness is released of external obligations. Engineer James Brindley would go to bed for several days when faced with a difficult problem. German chemist Kekule pondered the conceptualization of the benzene ring while napping:

> I turned the chair to the fireplace and sank into a half sleep. The atoms flitted before my eyes. Long rows, variously, more closely, united; all in movement wriggling and turning like snakes. One of the snakes seized its own tail and the image…. As though from a flash of lightning I awoke; I occupied the rest of the night in working out the consequences of the hypothesis (quoted in Beveridge 1957, p. 56).

Perhaps what can be learned here is that chance also favors the *relaxed* mind.

A frequently given example of a serendipitous moment occurred with bacteriologist Alexander Fleming. He was engrossed in examining different bacterial cultures when a spore landed in his uncovered Petri dish. Instead of disposing of the "contaminated" Petri dishes, Fleming recognized the unusual clearing around one of the bacterial cultures as indicative of suppressed bacterial growth. Fleming was amazed that out of thousands of molds, the mold penicillin inhibited bacterial growth (Roberts 1989).

Another example of a serendipitous moment resulting in a discovery is the story of Archimedes. Summoned by the king to determine if the majesty's crown was made of pure gold or of an alloy, Archimedes was presented with this problem to solve. A great mathematician of third century B.C., Archimedes determined, in order to solve this problem, the volume of the crown must be known—a feat considering the object's irregularity. While bathing in the public baths of Syracuse, he noticed the volume of the overflow of water was exactly equal to the part of his body placed in the tub. At this moment, Archimedes jumped up naked from his tub and ran through the streets screaming, "Eureka! Eureka!" Knowing the mass and now the volume of the crown, Archimedes could determine the density of the crown and compare this figure to the density of gold (it turned out the crown was not made of gold).

Serendipitous moments can also happen as a result of clumsiness: Charles Goodyear accidentally heated rubber with sulfur; the chemist, Fahlberg, spilled saccharin on his hand and tasted it; the worker who spilled a newly developed product (known later as Scotch guard) on a tennis shoe noticed its repellence to stains. Other moments can occur because of functional purposes. In 1974, Art Fry set out to make bookmarks and started considering other useful ideas with pieces of paper. He then stumbled across the idea of Post-it Notes (Roberts 1989). Other serendipitous moments include the development of the smallpox vaccine, the identification and isolation of insulin, the discovery of Pluto's moon, Teflon, Velcro, X-rays, and many other phenomena. Albert Szent-Gyorgyi eloquently states, "Discovery consists of seeing what everybody else has seen and thinking what nobody has thought" (quoted in Roberts, p. 245).

6.3.3 The Role of Thought Experiments in Inquiry

Another way to conjure new ideas or theories is through "thought experiments." Time allotted for thinking is crucial for seeing patterns, making decisions, and improving scientific studies (Goodfield 1981). In this case, concepts are clarified and discoveries are made through rigorous thinking (Brown 2001). John Dewey calls mulling over ideas "reflective thinking" (1933). The main distinction between a trained and an untrained thinker is the ability to sift out irrelevant evidence. Beveridge (1957) describes the most effective investigators as those who conceptualize problems beforehand and design experiments to address these questions. Original ideas are more likely to arise with a depth of knowledge in the field and a breadth of knowledge in others. Scientists who have made significant contributions usually have wide interests in other fields, for example, Einstein.

"All creative thinkers are day dreamers" (Harding, quoted in Beveridge 1957, p. 55). Clerk Maxwell made mental pictures of every problem to stimulate the imagination (Beveridge 1957). Einstein also spent considerable time conceptualizing aspects of his theory of relativity through thought experiments, as indicated by his statement "From the beginning it appeared intuitively clear to me that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for the observer, who relative to the earth, was at rest" (Einstein 1944, p. 53).

Depending on the science discipline, the scientist's previous experience along with the type of questions asked can widely impact the methodological choices made when individual scientists conceptualize and embark on scientific investigations. Scientific disciplines also have different modes of inquiry. Physics, an older science, tends to be more theory-oriented whereas geology, a newer science, is heavily based on description. Scientific language within each discipline is also theory-laden; academic training and the reigning paradigms of the time shape scientists in their respective disciplines (Kuhn 1962).

6.3.4 Observation and Description as Scientific Method: The Role of Qualitative Research

In a well-developed science such as the physical sciences, abstraction is more common than in a newer science where description is the primary method of obtaining evidence (Knight 1986). The experimental method (the scientific method) is not appropriate in other forms of research such as descriptive biology, evolutionary biology, or observational ecology. In these studies, the scientist has limited control over extraneous variables. Examples of descriptive methodology include clinical observations, case studies, surveys, questionnaires, interviews, natural observation (with and without intervention), and archival studies (Sterner 1998). In medicine, descriptive analysis can be used to record symptoms of depression during antenatal and postpartum phases of pregnancy. An experiment is not conducted but rather clinicians gather responses from pregnant women in order to look for patterns in the data and to explain phenomenon (White and Frederiksen 1998). Jane Goodall (1967) was a pioneer in studying the behavior of chimpanzees. Because little was known about group behavior, foraging techniques, or caring for their young, Dr. Goodall used nonintervention methods and descriptive studies to record observations of chimpanzees in field notes. Within her field notes is a detailed description of chimpanzees' (*Pan troglodytes*) reaction to snakes that could never have been anticipated or would not have been discovered through experimentation.

In reality, scientists conjure several alternate hypotheses to explain phenomenon, a process called "brainstorming" (Gibbs and Lawson 1992, p. 146). Hypotheses are not entirely derived from observation but from past experiences (Gibbs and Lawson 1992; Kuhn 1962). Animal behavior expert Tim Caro investigated gazelles' slotting behavior (the tendency to leap into the air) in Kenya's Serengeti Plain (1986). Caro conceptualized multiple hypotheses on slotting and gazelles based on his past experiences with predator-prey relationships. His hypotheses included the possibility that gazelles slot to (1) warn other gazelles about the danger, (2) draw attention away from the vulnerable offspring, and (3) let the predator know it has been seen. Questions can generate different lines of inquiry such as an *exploratory study* where the scientist observes the behavior of gazelles and records detailed notes in a field notebook. In a *correlation study*, the scientist after observing gazelles slotting records possible factors affecting the gazelles' behavior. Finally in an *experimental study* the scientist narrows down possible causes for the behavior and conducts a study to determine the most robust explanation based on the evidence.

6.3.5 Experimentation in Inquiry

In correlational studies, scientists try to determine if a relationship exists among the variables, not if one causes the other (Sterner 1998). Relationships can be graphed on scatterplots to indicate positive or negative correlations (Fraenkel and Wallen 2000). Correlational studies also serve as predictors for determining the likelihood of a variable affecting another. Once a relationship is established, experimental methods can *then* be used to determine causality.

The most frequently portrayed process of science is the experimental method. This research practice determines cause and effect relationships through organizing a controlled experiment with the goal of manipulating one variable at a time and measuring the outcome. Experimental research is the most commonly portrayed version of science in textbooks but this limited portrayal omits the diverse pathways to scientific progress as previously discussed (Bauer 1992; Gibbs and Lawson 1992; Brush 1976; Medawar 1963).

Modifications to lesson plans can help diversify scientific inquiries and illustrate the multiplicity of scientific processes through the following instructional strategies: the inquiry wheel, narratives, re-enactments, out of class problem solving, discussions, debates, analyzing quotes, and revamping assessments. These adjustments can supplement a science textbook to expand and revive science to a lively process characterized by controversy, nonlinear pathways, diverse research methods, unplanned realizations, reflection, persistence, imagination, open-mindedness, and creativity. Science is portrayed as lifeless in textbooks because inquiry is omitted as a vital function. Without inquiry science would remain in a state of inertia.

6.4 Conclusions

Helping students understand that there are many diverse pathways scientists use to reveal knowledge about the natural world ensures learners see these as part of their classroom experiences. Doing so will increase the likelihood students will develop a conception of science more aligned with actual scientific practices. Instead of showing experimental methods as the sole or even primary means to scientific advancements students should experience a broad range of the paths scientists take or have taken as part of authentic scientific inquiry (Anderson 2002; NRC 1996, 2000; White and Frederiksen 1998; Bybee 1997; AAAS 1990, 1993; Klopfer 1969; Hurd 1969). Only through an authentic inquiry experience will we foster learners who can pose questions, seek evidence for and against claims, understand how to evaluate evidence, and understand science as a variety of processes by which the world can be understood. Students should not only be exposed to the fundamentals of a discipline but also to the attitudes of approaching and addressing inquiries necessary for scientific progress (Bruner 1960).

Simply exposing students to the “traditional” step-by-step scientific method is an incomplete representation of the range of applicable scientific processes that comprise inquiry. Unfortunately, the public view of scientific processes is faulty due in large measure to the misrepresentations of science textbooks. Scientists have clearly made the distinction between what they actually do and what is shown in textbooks, but science education has not explicitly incorporated diverse scientific pathways (thought experiments, correlational, descriptive, exploratory studies, and serendipitous moments) as part of a curriculum valuing what scientists do and how they think.

The linear, step-by-step image of the scientific method has become so ingrained in our culture that we need a commitment from curriculum developers, science educators, and teachers to dispel the myth of a single scientific method through diversifying scientific inquiries in textbooks and in science instruction. The result of scientific journeys is not to arrive at a stopping point or the final destination but to refuel with questions to drive the pursuit of knowledge. The use of the “inquiry wheel” and its sharp contrast with the static and linear presentation of method along with discussions and classroom experiences in various ways of inquiry knowing can be the force to reach this goal of science authenticity.

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