

TEACHING THE NATURE OF SCIENCE
Perspectives & Resources

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| Preface

Science pervades our culture. It informs—or purports to inform—social policy, from climate change and clean water to the safety of food, drugs, and workplaces. Science may also potentially inform personal decision making, from nutrition and weight-loss diets to energy-efficient appliances or eco-friendly products. Science educators thus have an important responsibility.

How do we prepare students for the challenges that lie ahead? What does effective science education look like?

In recent years, a public sense of urgency about achieving high-quality science education has fueled increased accountability in schools. In the current cultural and economic contexts, that has yielded more standardized tests. Given their inevitable format of multiple-choice questions, education has become reduced to memorizing itemized tidbits of knowledge. Teachers, obliged by circumstances to teach to the test, focus ever more on piecemeal content.

In the cases central to the ultimate aim of science education, however, the primary concern is less content than understanding the practice of science. Which claims are reliable, and why? Which experts can you trust, especially when they seem to disagree? Do the circumstances reflect a warranted change in scientific consensus? What are the possible sources of error and how do they shape the certainty of the claims? What assumptions may have been made and how might they bias the conclusions? Who sponsored the research, and what are the affiliations and interests of the researchers? Where does verifiable information end and value judgment begin? Namely: how do scientists arrive at their conclusions, and when are they thus worthy of trust? Students need to learn foremost about the *nature of science*, or NOS: how science works—or doesn't work—and why.

This book is a roadmap and resource on how to think about the nature of science. What fundamental analytical skills contribute to fruitful ongoing reflection, which might be nurtured in an educational setting? It is a guide especially for emerging teachers, although the perspectives may equally inform veteran teachers, teacher educators, researchers, curriculum specialists, textbook writers, science education administrators, museum educators, and others.

The strategy is unlike that of other books on the nature of science itself.

My aim here is not to survey the vast knowledge of the history, philosophy, and sociology of science (HPSS), although such knowledge is, in a sense, foundational. Nor is my aim to profile basic scientific methodology, or the principles of “good science,” particularly in contrast to pseudoscience or fraud. These approaches to learning NOS focus on content, too, but of a different kind. They are relatively unhelpful as an introduction.

Rather, my aim is how one can foster the development of thinking skills: ways to analyze and reflect fruitfully about NOS. The goal is for the teacher to develop a knack for *delving into NOS* and *asking important NOS questions*. Given a particular case, is one able to notice and highlight the relevant dimensions of science that affect the reliability of the claims? Can one interpret and articulate their significance? Can one identify further information that will deepen that understanding? The target is thus a repertoire of tools in NOS inquiry, not declarative knowledge. Ideally, a prepared teacher will be equipped to (1) serve as an explicit model for students, (2) guide others in their own emerging efforts, and (3) reflect further and continue to learn about the nature of science.

This strategy involves, in part, engaging the reader in new and different perspectives. To expand one’s analytical repertoire, one needs to open new ways of seeing. Some things may have always been there to see. By recognizing how to notice them, one can appreciate their significance more fully. One needs to learn, in a sense, how to probe the nature of science and to pose the appropriate questions.

Accordingly, the style of presentation here is chiefly by illustration, or demonstration through cases. Perspectives are *exhibited* and *articulated*. There are no formal abstract principles to elucidate, no arguments to master or dissect, no lists to memorize. This book does not resemble a conventional textbook in that sense, even while it endeavors to guide deep and meaningful learning. In style, it follows basic findings in cognitive science. Learning, here, is fostered through anomalies and paradigmatic exemplars and generalizing from them.

Of course, NOS conceptions abound among teachers and students, even without any explicit instruction. So cases that illustrate commonplace notions or conceptions already entrenched in our culture are not, in general, addressed here. At the same time, many widespread NOS conceptions—including those entrenched in the culture of teaching—are ill informed. There is much to *unlearn* about NOS. One must separate the wheat from the chaff. The focus here is thus selective, especially in targeting caricatures and naive conceptions. Further, in adopting a pedagogical constructivist perspective, most examples mindfully challenge the NOS preconceptions that are ill informed. Other examples consider teaching methods that seem intuitive to some but that, ironically, prove ineffective or even counterproductive. The overall posture may seem critical. Still, the intent is to motivate reflection and conceptual growth. Individually and collectively, the essays may seem to

challenge many assumptions or practices. Yet this is precisely where one may expect genuine learning to occur.

The book is also incomplete in many ways. Learning involves engagement. Thus, ideally, the reader will couple reading of the text with an extended exploration of at least one case in the history of science. The perspectives introduced here become vivid when applied to and measured against real science. Appreciation of the many dimensions of NOS will be greatly enhanced by familiarity with the concrete details of one case. This, too, follows an educational approach that highlights the value of depth.

Some educators believe that the primary or best way to learn about scientific practice is to become a scientist oneself. Yet this may overstate the goal. Yes, every individual should develop some basic investigative skills that enable them to troubleshoot a lamp that does not light, say. They should be able to read simple graphs and evaluate simple data charts. But dealing with evidence at an elementary level is not sufficient for interpreting most science today: for example, the complexities of climate change models, or vast meta-analyses of the significance of mammograms at different ages. Students, like scientists themselves, must rely on the expertise of others. One must learn to be a prudent consumer of science: interpreting the difference between science that is well done and that which should be regarded skeptically or jettisoned outright. The relevant dimensions of scientific practice extend well beyond what one might expect individual students to perform themselves.

One may develop an understanding of the practice of science in many ways. The primary ways are through (1) a student's own labs or inquiry activities, (2) contemporary case studies, and (3) historical case studies. I will not have much to say about student investigations: this is familiar territory for most teachers (including from their experience as students). My primary focus is the role of historical cases (see Chapter 2). Indeed, I contend that deeper appreciation of historical case studies—when styled in an inquiry mode or problem-based format (Chapter 14)—provide deeper, more complete lessons. Indeed, they may well inform how a practicing teacher guides student reflection in the other two formats.

Another major emphasis in contemporary discussions of NOS education is profiling the nature of models and the process of model building. The theme has an important deflationary function, qualifying widely held popular views of the monumentality of scientific theories. Models have been and continue to be important tools in science. But not all science is model driven or explanatory in nature (see Chapter 1). The current enthusiasm for models carries the traces of a short-lived educational fad. One would do well to disregard the hype and focus just on the enduring features of models that have been acknowledged by philosophers of science for decades (see Chapter 8). Thus, while a model-based perspective complements and provides an important context for the themes discussed in this volume, I leave the articulation of that theme to others.

Nearly all the material in this book has been published elsewhere. It seemed appropriate, however, to bring it together in a single volume and present it as a coherent constellation. In addition, I have rewritten and updated every chapter to convey a more unified vision of teaching the nature of science. I have added cross-references and additional comments to underscore their integrated themes and enhance their integrity as an ensemble. In particular, I address topics that are overlooked elsewhere and stress themes that probe common yet misleading cultural conceptions. It is not a comprehensive, “textbook” introduction to the field. Still, one should find the basic tools for NOS reflection here, along with methods for empowering students with those tools, to promote self-guided NOS learning.

In assembling this volume, I have drawn on a unique cross section of experience in science teaching, scientific research, and advanced study in the history and philosophy of science. I taught high school biology for several years, both introductory and AP levels, and later introductory college biology at several institutions. One interdisciplinary science course was structured as an episodic history of science, supplemented with historically inspired labs. I have also participated in research at three biological field stations: looking at treegaps and forest succession in a mid-Atlantic forest; mapping long-term succession in a tropical rainforest; and measuring sexual selection in flowers through the differential transfer of pollen in meadows of the Rocky Mountains. I certainly recommend to any science teacher the exhilarating and enriching experience of living and working in a research community for a season. My own work for a master’s degree in evolutionary biology focused on a mathematical model for information-center foraging, such as one finds in honeybee hives, ant societies, and many bird colonies. I couple this firsthand experience with a Ph.D. in the history and philosophy of science from the University of Chicago—and I continue to publish scholarly articles in these fields (from the *Dictionary of Scientific Biography* and an examination of eighteenth-century geologist James Hutton’s views on coal, to analyses of disagreement in science, error types, and the conceptual dilemmas of Mendelian dominance). Many of my students in undergraduate history and philosophy-of-science classes have been en route to careers in science teaching, and it is rewarding to shepherd them to deeper understanding of, and reflection on, scientific practice. Through these diverse experiences, I have gained immense respect for science teachers, scientific researchers, historians, philosophers and sociologists of science, and, above all, students. I hope the present volume offers a fruitful synthesis, integrating and honoring these multiple contexts.

The contents of this book are presented in two sections. In the first, I provide perspectives for deepening an awareness and appreciation of NOS. The second section profiles some sample classroom case studies in several disciplines, each with supplemental pedagogical commentary.

In Chapter 1, I survey the territory ahead. In part, I address a large handful of NOS preconceptions, especially common among science teachers, hoping to clear the field of some entrenched notions that make deeper understanding more problematic. The project is expansive: tracking the assembly of scientific knowledge from laboratory or field observations to public communication of science. Reliability is at stake at every step along the way. And the scientifically literate citizen needs to be ready to cope with any of them. In Chapter 2, I describe the relevance of history and inquiry-type historical case studies to the task. In Chapters 3–5, I profile several challenges of using history effectively and, thus, portraying NOS faithfully. These include the problems of myth-conceptions, rational reconstructions, and ideologically shoehorned pseudohistory. In Chapters 6–8, I elaborate on important views of nature and science that are currently unduly peripheralized: the role of culture, the tendency for simplification to drift into oversimplification, and the dominating image of laws in science. In Chapter 9, I address the challenge of assessing NOS understanding, so critical in our current age of accountability.

In Chapters 10–13 (Part II), I present a sampling of case studies as exemplars—showing just what it means to use history to teach nature of science. These are both ready-to-use resources and models for developing such resources. Chapter 14 introduces a sample of other fine case studies, provides a guide for assessing yet others, and offers a framework for the novice case-study author. While these concrete resources are closer to classroom practice, the conceptual perspectives offered in Part I are critical to understanding how the NOS lessons are structured and how to use them fruitfully.

Those who wish to pursue the topics of this book further, who seek additional concrete resources for teaching as profiled here, or who want to continue the educational dialogue on NOS are invited to explore the SHiPS Resource Center, a website that I developed and have edited for the past two decades: <http://ships.umn.edu>.

CORRECTION: "The Scientific Method" is often taught in science courses as a simple way to understand the basics of scientific testing. In fact, the Scientific Method represents how scientists usually write up the results of their studies (and how a few investigations are actually done), but it is a grossly oversimplified representation of how scientists generally build knowledge. The process of science is exciting, complex, and unpredictable. It involves many different people, engaged in many different activities, in many different orders. To review a more accurate representation of ...¹ That's the nature of scientific knowledge " it's inherently tentative and could be overturned if new evidence, new interpretations, or a better explanation come along. Teaching and Assessing the Nature of Science. we emphasize that a philosophical position about the nature of science is more than a list of tenets.² Because science is such a complex and varied activity, rather than listing specific NOS ideas students should learn, NOS issues should instead be addressed as questions (Figure 2; Clough 2007).³ between basic science, applied science, and technology. uu Articulate why science explains natural phenomena in naturalistic terms with no recourse to the supernatural. uu Provide arguments against a universal scientific method. uu Explain how imagination and creativity are crucial in doing science. uu Explain how scientists develop ideas to account for data, and how data does not tell scientists what to think. uu.