THE NATURE OF SCIENCE: FROM TEST TUBES TO YOUTUBE

DOUGLAS ALLCHIN, DEPARTMENT EDITOR

Climategate. Erroneous links between the measles vaccine and autism. Revised mammogram recommendations. Suspect communication with coma patients. Such cases in the news in the last year are striking because biological knowledge will not help the typical citizen interpret the key issues. One needs to understand instead the *nature of science* (NOS): Whose expertise can be trusted, especially when experts seem to disagree? What public presentations of scientific findings are credible? How do scientists manage data? How do they communicate with each other? What conditions warrant a change in scientific consensus? How do value judgments relate to verifiable information? How might scientists make "honest" mistakes, and how does one detect them? These cases exemplify vividly the educational goal of scientific literacy – here, to use knowledge *about how science works* to inform real-life decisions, both personal and public. Knowledge of NOS may be as important as – if not more important than – knowledge of content.

Approaches to NOS in education harken back to the 1960s, at least (Lederman et al., 1998). By the mid-1990s, amidst various reforms, the characterization of NOS seemed to reduce to a tidy list of 8 to 10 simple concepts (AAAS Project 2061, 1993; McComas, 1996; McComas & Olson, 1998; National Science Teachers Association, 2000; Osborne et al., 2003). For example: science is tentative; scientists are creative; observations are theory-laden; science is affected by its social and cultural milieu (Lederman et al., 2002). The list has become a largely uncontested consensus. Another sacred bovine, perhaps? Here, I review how such tenets inform the cases above, as touchstones. That leads to a simpler, more coherent way to characterize NOS – one that is also more practical in terms of teaching and evaluating student understanding (for fuller discussion, see Allchin, 2010).

○ 'Tentativeness' & Its Dangers

One of the recurring themes in NOS discussions is the provisional nature of scientific knowledge. Theories may change or be abandoned as wrong. Without the "test of time" and further scrutiny, science remains partly uncertain. Even well-accepted theories may be revised with new perspectives or new evidence. The key word is typically 'tentativeness.' As our knowledge grows, concepts are not only added; they may also be replaced or rejected, sometimes quite dramatically.

As the mammogram case illustrates, scientific consensus can not only change, but the change can also be profoundly relevant socially. As the vaccine case shows, individual scientific studies – even if published – may be incomplete and their conclusions later invalidated. Here, individuals acting on premature conclusions led to a significant public risk of a measles epidemic in Britain. Understanding tentativeness is surely important to functional scientific literacy.

But other familiar cases indicate how the concept may be misinterpreted and misappropriated. Consider the bane of biology educators: anti-evolution critics. When creationists advocate "teaching the controversy" (or affixing warning labels on textbooks), they implicitly appeal to a principle of uncertainty, or tentativeness in science. In his creationist diatribe *Icons of Evolution*, Jonathan Wells (2000) opined that Darwinists are closed-minded, dismiss simple evidence, and thus fail the norm of skepticism in science. He derided Darwinists as "dogmatic" *twenty-three* times in the final chapter alone. Wells presented this concept as reason to question evolution, like any science. Ironically, tentativeness has proved to be powerful rhetoric in promoting *misunderstanding* of the nature of evolutionary science.

Consider also the case of global warming. Despite the scientific consensus expressed by the Intergovernmental Panel on Climate Change (IPCC), skepticism has dominated American politics. Critics cite patchy data, uncertain models based on numerous assumptions, the unpredictability of the daily weather, isolated results that contradict general conclusions, the newness of climate science, the limitations of peer review, et cetera. Note the telltale catchphrase of ClimateChangeFraud.com: "Because the debate is NOT over." It seems to delight in quoting Mark Twain: "There is something fascinating about science. One gets such wholesale returns of conjecture from such a trifling investment of fact" (http://www.climatechangefraud.com/temperate-facts/co2-and-gw-primers/global-warming-q-a-a?start=1). In the skeptics' rhetoric, climate science suffers from uncertainty, incautious overstatement, and premature conclusions.

Of course, these are not the voices of reliable science. A recent study confirmed that the scientists unconvinced about climate change are typically in peripheral fields and their work is far less widely cited (Kintisch, 2010). Indeed, as documented by Naomi Oreskes and Erik Conway (2010), the public doubt has been deliberately orchestrated by just a handful of politically connected scientists. Their strategy has been to generate and leverage an image of uncertain, still actively debated science. That has been enough to stall political action. The tactic is not new. Earlier, the same group capitalized on tentativeness to mislead the public on secondhand smoke, acid rain, the ozone hole, and DDT. If all one learns is that "science is tentative," mischief remains possible.

These cases illustrate that merely acknowledging science as tentative is insufficient. The label can backfire if not understood fully. Nature of science is not defined by a list of abstract, general academic declarations. Understanding needs to be functional and concrete. Here, it is helpful to recall the broader goal of scientific literacy as context:

> *Students should develop a broad understanding of how science works to interpret the reliability of scientific claims in personal and public decision-making.*

Students need to be able to interpret scientific practice in *particular* cases, not abstractly. A short list of principles to memorize or explain is simply inadequate. NOS is not diluted philosophy of science (AAAS Project 2061, 2009).

○ Interpreting Climategate

Consider more fully the case of Climategate. In November 2009, someone anonymously released e-mails hacked from a university server, written by

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a leading member of the IPCC. They included comments about scuttling efforts to release data under the Freedom of Information Act, a "trick" used to graph data, and ways to limit publications by critics. James Delingpole, in a blog for England's *Telegraph*, promptly dubbed it "Climategate." Skeptics proclaimed vindication of their allegations of fraud and collusion.

One can just imagine the scene at the lunch table: one coworker sighs how the case just proves that global warming is a hoax, while another contends that scientists don't do things like that and that the posted documents themselves are probably fraudulent. Mutual epithets fly across the table, and the person in the middle is asked to settle the matter. Here is a prime example of a role for scientific literacy.

Now, what NOS concepts does one need to interpret this case effectively? The central issue here is credibility (not tentativeness). But credibility is not addressed in the current NOS consensus. Well then, does it help to know the difference between a law and a theory? No. How about the nature of an experiment? Well, not really. "Science can be shaped by its social milieu"? Perhaps, but political bias could well influence both views. Has it? One needs analytical tools, not general tenets.

To interpret Climategate, one needs to know instead about

- the spectrum of personalities in science
- the nature of graphs
- the norms of handling data
- how scientists communicate
- credibility and expertise
- robustness of evidential networks
- fraud or other forms of misconduct

NOS includes the whole spectrum of features that affect the reliability, or trustworthiness, of scientific claims. One cannot responsibly escape teaching any relevant factor. When one considers the diversity of cases that emerge in contemporary society (such as those noted at the outset), one finds the current NOS lists imprudently truncated.

○ Mapping NOS

The nature of science (as part of scientific literacy) is foremost about how science works. Yet scientific practice is multifaceted – potentially confusing and overwhelming. One thus needs a simple conceptual framework to organize all its features. A structure that extends well beyond the traditional "scientific method" (http://undsci.berkeley.edu/article/scienceflowchart) and includes, for example, funding, biographical contexts, social networks, gender, and science journalism. Any factor that may shape reliability.

A simple yet synoptic approach tracks the genesis and movement of scientific claims from local to global domains. From the lab bench to the judicial bench. From the calibration of instruments to the contexts of cognition and cultural criticism. Generating knowledge requires care at each step. Any one element can be a source of error, if not addressed properly. Features of NOS thus encompass the development of a scientific claim from experimental controls, through the revision of theories, to publishing in journals and communicating science in the public media. From test tubes to YouTube (Figure 1).

Call it Whole Science. In contrast to unhealthy, highly processed and refined "school science." Figure 1 organizes the dimensions of reliability on two levels. At a general level, the scope of claims ranges from relatively narrow conclusions in a laboratory (no. 1) to broader theories that synthesize large amounts of observations and data to those that are disseminated widely to

1. Observations & Reasoning
- evidential relevance (empiricism)
- role of systematic study (versus anecdote)
- completeness of evidence
- robustness (agreement among different types of data)
- role of probability in inference
- alternative explanations
- verifiable information versus values

2. Methods of Investigation
- controlled experiment (one variable)
- blind and double-blind studies
- statistical analysis of error
- replication and sample size
- correlation versus causation

3. History & Creativity
- consilience with established evidence
- role of analogy, interdisciplinary thinking
- conceptual change
- error and uncertainty
- role of imagination and creative syntheses

4. The Human Context
- spectrum of motivations for doing science
- spectrum of human personalities

5. Culture
- role of cultural beliefs (ideology, religion, nationality, etc.)
- role of gender bias
- role of racial or class bias

6. Social Interactions among Scientists
- collaboration and competition among scientists
- forms of persuasion
- credibility
- peer review
- limits of alternative perspectives and criticism
- resolving disagreement
- academic freedom

7. Cognitive Processes
- confirmation bias/role of prior beliefs
- emotional versus evidence-based perceptions of risk

8. Economics/Funding
- sources of funding
- personal conflict of interest

9. Instrumentation & Experimental Practices
- new instruments and their validation
- models and model organisms
- ethics of human subject experimentation

10. Communication & Transmission of Knowledge
- norms of handling scientific data
- nature of graphs
- credibility of various scientific journals and news media
- fraud or other forms of misconduct
- social responsibility of scientists

Figure 1. Nature of science: dimensions of reliability in science.

the public (no. 10). One may frame 10 convenient categories. Second, within each category are specific concepts and methods. Effective NOS instruction will achieve both breadth and depth. Over 13 years students need to develop awareness of these categories and analytical skills in each.

NOS understanding in a Whole Science approach echoes familiar, but often intuitive and implicit, goals in science teaching. For example, analyzing the credibility of sources on the Internet or in other public media (no. 10) is a common lesson, yet rarely listed on the formal curriculum. Here, the NOS scheme clarifies how it relates to the more standard lessons on controlled experiment (no. 2) or peer review (no. 6). This approach also provides further justification for discussing current issues in the classroom. The unifying theme is the *reliability*, *trustworthiness*, or *authority* of scientific claims. What students need to learn above all is how to judge what (or who) to trust – and why. Ultimately, Whole Science can simplify NOS approaches. And free teachers to delve into *any* case of real scientific practice – and discuss *whatever* details may prove relevant. The catalog simply provides a reference guide for assessing the completeness of one's teaching about scientific practice.

All this leads, of course, to exciting new challenges: how to teach Whole Science and then how to evaluate student understanding of NOS. Overwhelming? Not really. But there are more sacred bovines lurking on the path ahead – to be addressed in the next two issues.

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DOUGLAS ALLCHIN has taught both high school and college biology and now teaches History of Science at the University of Minnesota, Minneapolis, MN 55455; e-mail: allchin@sacredbovines.net. He is a Fellow at the Minnesota Center for the Philosophy of Science and edits the SHiPs Resource Center (ships.umn.edu). He hikes, photographs lichen, and enjoys tea.