TEACHING THE NATURE OF SCIENCE

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Understanding the nature of science (NOS) is widely perceived to be a vital learning outcome of science education. But is it necessary to include this in the school science curriculum? Do we introduce school students to its evolving perspectives? What pedagogical approaches can help teach NOS?

Most science textbooks begin with an introductory chapter on the nature of science (NOS), devote a few paragraphs to it, then quickly move on to what is regarded as the main stuff of science—its empirical facts, laws, theories, etc. Naturally, this raises the question—why is it necessary to teach NOS when there is so little time to finish the 'more important' parts of the subject?

Why teach NOS?

Science is a compulsory subject till the end of secondary school. At this stage, most students end their engagement with the formal education system. Among those who pursue higher education, only a small fraction chooses to continue in the science stream. A smaller fraction of this number goes on to choose professions (like that of a research scientist) that need a robust understanding of science and its applications. This means that the scientific content knowledge taught in school is unlikely to be of direct help to the professional lives of a majority of middle and high school students. Then why is science education compulsory at the school level? Clearly, this would make sense only if its main purpose was somewhat broader than imparting specific science content.

While the goals of school science education have been debated endlessly, often from differing ideological stances, few would disagree that a principal goal is to generate an informed science citizenry. It is important for students to grow into citizens who have a feel for what science is about, what methods and processes are involved in generating new science, and how science is related to technology and society. For example, some would argue that science can help encourage a rational outlook on life. Others may argue that it is becoming increasingly necessary for us to become familiar with modern technology—its benefits, risks, impacts on our health and environment, etc. Given the many ways in which science and technology impact our lives today, this familiarity can help us formulate more mature opinions about these issues and make more informed choices. These and several other allied objectives are sometimes clubbed under the head 'science and technology literacy'. There are numerous variants of this term as well as many shades and nuances, but it may be safe to say that the rationale for teaching NOS is tied closely to this general goal of school science education.

Does this mean that we incorporate the teaching of NOS at the expense of the 'real' content of science? In doing so, do we not jeopardise the quality of knowledge of future scientists? Will our country not lose out on its competitive edge in science? Also, will the teaching of NOS be of any real use to the large majority of students we have in mind? These concerns, widely shared among teachers (and scientists), arise mainly because there is not enough clarity on how the teaching and learning of NOS is relevant to the rest of the science curriculum.

First, it is inaccurate to suppose that NOS is relevant only for students who end their formal engagement with science in Grade X, or that it is irrelevant for students training to be future scientists. Many detailed studies show that the epistemic and ontological beliefs that students hold about their subject have a bearing on their critical understanding of the content itself. This suggests that understanding NOS is relevant not only in meeting the general goal of promoting science and technology literacy but also in helping science students develop a deeper understanding of this subject. Secondly, what is envisaged is not to 'dilute' the content of science, but rather to use it imaginatively as a means to teach NOS. In other words, NOS is to be taught not by preaching abstract generalities set aside in a separate unit of the textbook, but by interleaving it with the content of science.

What to teach?

The few paragraphs that textbooks devote to NOS typically state some version of the following: *'Science involves a process of making systematic unbiased observations of nature, doing careful experiments, and drawing logical inferences from them. In this way, we arrive at the laws of nature. We suggest hypotheses to understand empirical laws, which leads us to build elaborate theories to explain known physical phenomena. Theories also predict new phenomena. If the predictions are verified, the theory is confirmed. Science bows to no authority; it is objective knowledge obtained from observations and experiments'.* There is much that makes sense in this description of NOS, simplistic though it will seem as we discuss it further.

NOS has been the subject of philosophical inquiry all through history and continues to be so even today. Rapid advances in science in the last four centuries have led to many active discourses on our ideas on NOS (see **Box 1**). These have led to some new insights. First, science is not just a

Box 1. Emerging Perspectives on NOS:

Modern science emerged in the 16th and 17th centuries from the work of Galileo, Descartes, Kepler, and Newton. It was at this time that Francis Bacon, an English philosopher, formulated what is now known as the scientific method (see **Fig. 1**). Roughly speaking, the introductory paragraphs of school science textbooks replicate Bacon's ideas on NOS. The essence of Bacon's ideas is that science is an inductive generalization from unbiased observations of nature and controlled experiments. Bacon foresaw the immense power of this new method in predicting and controlling natural phenomena.

At the beginning of the 20th century, an influential group of philosophers of science known as the Vienna circle (that included Moritz Schlick, Rudolph Carnap, and others) undertook the effort to formulate a more rigorous version of the scientific method. Briefly, they regarded a statement or an assertion meaningful only if it was either logically self-evident or could be put forth in a verifiable form. This meant that while one may use theoretical terms like 'atom', 'gene', and 'valency' for convenience, all scientific concepts and assertions must ultimately be reducible to observation statements. By this strict criterion, for example, poetry was considered meaningless and harmless, while a metaphysical assertion was meaningless but harmful (since it purported to be true). However, the proponents of this philosophical position, called logical positivism (and later, in a more moderate version, logical empiricism), could not realise their ambition of translating all of science in these terms.

Fig. 1. Francis Bacon formulated the scientific method.

At around the same time, the Austrian-British philosopher Karl Popper suggested a philosophical position that was also in the spirit of analysing the scientific method, but distinct from logical positivism in many ways (see **Fig. 2**). Popper was driven by a desire to differentiate between 'science' and what he regarded as 'pseudoscience'. He is most widely known for his falsification criterion—a theory is not scientific if there is no way to refute it. Good scientific theories give unambiguous predictions that are falsifiable. This means that verification of these predictions does not confirm the theory; the theory is simply shown to not be false yet. Inspired by Einstein's work, Popper advocated that science should 'stick its neck out', give bold new predictions, and suggest critical experiments that have the potential to falsify a theory. Popper's ideas resonate with scientists, and he is often called the scientists' philosopher.

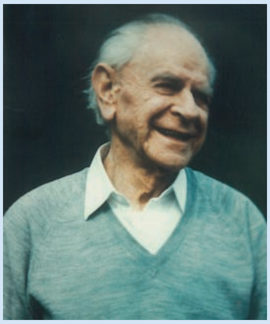

Fig. 2. Karl Popper is most widely known for the falsification criteria.

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Around the 1950s, the American philosopher Willard Van Orman Quine offered an incisive criticism of these dominant ideas. He argued that a scientific theory is a complex web of interconnected assumptions and claims that relate to experience as a whole. Consequently, it may not be possible to test or falsify each statement of the theory in isolation. He called for a holistic theory of meaning and testing.

Philosophies seeking a rational basis for science separated the context of discovery (the intuitive creative phase of science embedded in specific social settings) from the context of justification (critical philosophical scrutiny of theories claimed to be correct). Since the former was believed to belong to the realm of psychology or sociology, it was seen as being beyond the purview of science.

Around the 1960s, the American historian and philosopher Thomas Kuhn published his now-famous book, titled 'The Structure of Scientific Revolutions' (see **Fig. 4**). This book marked the beginning of a major transformation in our ideas on NOS. By analysing some key milestones in the history of science, such as the Copernican revolution, Kuhn concluded that scientists normally work within a certain paradigm. They are conservative in that they do not abandon existing theories in the face of minor anomalies or disagreements with experimental data. However, stark anomalies that accumulate over time cause a crisis in the normal process of science and lead to questioning of the existing paradigm. All kinds of alternative ideas float around during such periods of crisis. Some promising new ideas begin to attract consensus, often because of some particularly striking exemplars. In this manner, a new paradigm is born. This leads to a return to 'normal' science, with scientists attempting to work out details and applications of the changed paradigm. Significantly, the paradigm shift that Kuhn refers to is not governed by a purely rational process. It involves the building of a social consensus in the scientific community at large. Adherence to a paradigm that has won the consensus of the scientific community at a certain point in time is secured by training students in colleges and graduate schools in accordance to it.

Not everybody agreed with Kuhn. On the one hand, the Hungarian philosopher Imre Lakatos found the undermining of the rational basis of scientific progress implied in Kuhn's ideas unacceptable. Lakatos went on to develop a theory that explained paradigm shifts in science in terms of competing 'research programmes'. On the other hand, the Austrian philosopher Paul Feyerabend dismissed the idea of there being a clear method in the way science evolves. The idea of a normal process of science had a very significant role in Kuhn's perspective. He believed that it is this process that delves deeply into an accepted paradigm, making it possible to discover anomalies that eventually result in a change in the paradigm. Feyerabend, in contrast, criticized the routine mind-numbing activities of normal science. He asserted that science progresses through creative leaps of imagination that defy existing ideas. Feyerabend's philosophy is often summarized by the catchy phrase 'anything goes'. His noted book 'Against Method' celebrates creativity in science and advocates the freedom of imagination. Thus, while Lakatos found the disorder inherent in Kuhn's view of science alarming, Feyerabend criticized Kuhn's view for its orderly and mechanical view of scientific progress.

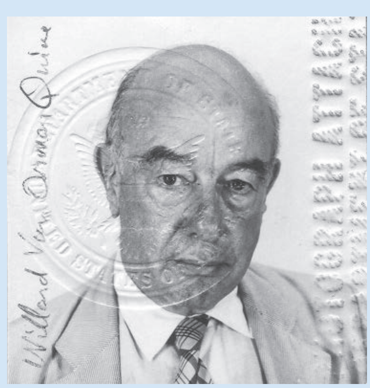

Fig. 3. Willard Van Orman Quine argued that a scientific theory is a complex web of interconnected assumptions and claims that relate to experience as a whole.

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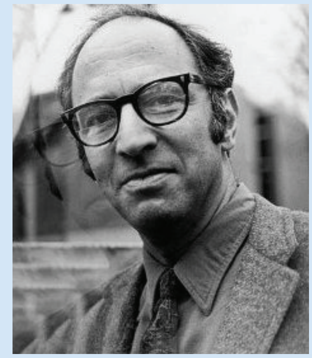

Fig. 4. Thomas Kuhn suggested that scientific fields undergo periodic 'paradigm shifts'.

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Whatever its merits, Kuhn's theory was responsible for the introduction of a sociological dimension to the philosophy of science in the second half of the 20th century. Indeed, some sociologists found the standard philosophy of science irrelevant. They asserted that NOS could be understood only by a critical and detailed probing of the actual way in which scientists work. This development has pushed the debate on NOS into many different directions that cannot be adequately described here. What is possible, however, is to acknowledge the role this development has had on our understanding of the sociocultural norms that enable progress in science. It is clear, for example, that the formation of robust social institutions of science (notably scientific societies in Europe, such as the Royal Society) that practised norms of open and democratic discussion, peer review of research, and common ownership of scientific laws was as crucial in the growth of science as the ingenuity of individual scientists.

process of induction from observations and experimental data. It often involves imaginative and radical new ideas that are not necessarily suggested by empirical evidence. Some of the most successful theories of science have arisen, for example, from a drive for unification or general considerations of simplicity and symmetry. Second, though observations of nature are often the starting point of all scientific inquiry, not all observations are neutral. They are often 'theory-laden'. This means that theories implicitly or explicitly guide what we observe and the kind of experiments we design. This does not necessarily undermine the objectivity of science. Third, observations and experimental data underdetermine correct theories; several different theories can all be consistent with them. Fourth, science is not a purely cognitive endeavour. While it is certainly constrained by the empirical facts of nature, science involves some social consensus among scientists. It also requires enabling sociocultural norms and conditions for its growth. Fifth, science, technology, and society are intertwined in complex ways—impacting and being impacted by one another. As a corollary to this, it is important to be alert to possible pitfalls in scientific practice as well as the harmful consequences of the uncritical and unwise use of technology.

With so much of the historical debate on NOS continuing into the present, what is it that we would wish for students to learn about it in school? While a wide range of perspectives and complex philosophical positions are related to NOS, it is widely believed that a core of generally accepted new ideas is learnable by young students. This can be used to frame some broad objectives for the school science curriculum. To briefly highlight these, NOS should help students appreciate the following aspects of science:

- **Scope:** Science seeks to describe and explain the physical world based on empirical evidence. Some domains may be beyond its scope.
- **Methods:** Science adopts a variety of approaches and methods. There is no one universal method of science. It does not involve induction alone. Creativity and imagination are equally important in generating hypotheses and building theories. Observations and experiments are often insufficient to determine a theory. Science involves expert judgments and not just logical deductions. Hence, there can be disagreements in science.
- **Social aspects:** Science is a cooperative multicultural human enterprise that includes contributions by countless women and men, including some noted individuals who play a significant role. Social institutions that practice norms of open debate, peer reviewing, and common ownership of knowledge are also vital for the growth of science. Links between science and technology may lead to issues that need sociocultural resolution.
- **Scientific knowledge:** This is dynamic and subject to revision in the face of new empirical evidence.

How to teach NOS

The most important but difficult question related to NOS is—what pedagogy do we use to teach it at the school level? The idea that content alone is not enough in science education is not new. This is seen in the history of curriculum reforms since the 1960s (or even earlier). Around the 1970s, some educational reforms emphasized the importance of teaching processes of science more than just its content. These included—observing, measuring, classifying, analysing, inferring, interpreting, experimenting, predicting, and communicating. However, in critical appraisals of this approach, some educators have questioned the premise that these constituted a set of general transferable processes common to all sciences.

For some time now, there seems to be a broad convergence on an inquiry-based approach to science learning and teaching. Informed by the constructivist philosophy, this approach does not just involve learning the processes of science; but extends beyond to include skills such as posing questions, critical thinking, giving evidence-based explanations, justifying explanations, and connecting explanations to existing scientific knowledge. In other words, this approach advocates that students learn science in a manner that resembles the way in which professional scientists conduct scientific investigations. This involves designing a range of inquiry tasks, all of which pose a question and seek an evidence-based explanation. These tasks can be relatively simple for younger children and quite elaborate for more mature students. They can have different foci—some may relate to Science, Technology, and Society (STS) issues, while others may be more discipline-oriented. An inquiry may also include reflections on the mode of inquiry itself and, thus, naturally incorporate the educational objectives of NOS.

Another approach recommends the use of the History of Science (HOS) to teach NOS. While this too is not a new idea, some key points in its favour are:

- HOS involves human narratives which enliven science and engage students' interest.
- HOS often has parallels with students' spontaneous conceptions and thus helps us in anticipating and remedying their content-specific ideas.
- Knowing how present science arose from competing ideas at different times in history can promote critical thinking.
- Lastly, HOS provides the most natural setting for learning NOS.

Parting thoughts

As Norman Lederman, a Distinguished Professor of Mathematics and Science Education at the Illinois Institute of Technology (IIT), has forcefully argued, NOS objectives should be regarded primarily as cognitive outcomes that can be properly assessed. Since these objectives are unlikely to be assimilated implicitly, instruction needs to bring them out explicitly, irrespective of whether we adopt an inquiry-based or history-based approach to do this. In other words, a whole range of inquiry tasks and HOS-based vignettes that are explicitly focussed on NOS need to be developed if we aim to improve student understanding of NOS.

Key takeaways

- Numerous studies show that the nature of science (NOS) is relevant not only in meeting the general goal of promoting science and technology literacy but also in helping science students develop a deeper understanding of this subject.
- NOS is to be taught not by preaching abstract generalities set aside in a separate unit of the textbook, but by interleaving it with the content of science.
- What is taught about NOS at the school-level should help students appreciate the scope of science; its many methods and approaches, including the role of expert judgments and the possibility of disagreements; the social aspects of this cooperative multicultural human enterprise; and the dynamic nature of scientific knowledge.
- Two pedagogical approaches—Inquiry-based and History of Science (HOS) based—are recommended to teach NOS at the school level.
- NOS objectives need to be regarded primarily as cognitive outcomes that are explicitly drawn out by instruction and can be properly assessed.

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References:

1. Godfrey-Smith P (2003). 'Introduction to Philosophy of Science'. The University of Chicago Press: Chicago.
2. NGSS (2013). 'Next-generation Science Standards: For States, by States'. Appendix H. URL: www.nextgenscience.org.
3. Pumfrey S (1991). 'History of Science in the National Science Curriculum: a critical review of resources and their aims'. British Journal of the History of Science. 24, 61–78.
4. Osborne J, Ratcliffe M, Bartholomew H, Collins S, & Duschl R (2002). 'EPSE Project 3: Teaching pupils ideas-about-science'. School Science Review, 84 (307), 29–33.
5. Taylor JL & Hunt A (2014). In Matthews MR (ed.) op. cit. 2045-2082. 'History and Philosophy of Science and the Teaching of Science in England'. Springer: Dordrecht, Netherlands.
6. Erduran S & Dagher ZR (2014). 'Reconceptualizing the Nature of Science for Science Education'. Springer: Dordrecht, Netherlands.
7. Millar R & Driver R (1987). 'Beyond Processes'. Studies in Science Education, (14) 33–62.
8. Flick LB & Lederman NG (eds.). (2006). 'Scientific Inquiry and Nature of Science'. Springer: Dordrecht, Netherlands.
9. Holton G & Brush SG, 3rd ed. (2001). 'Physics, the Human Adventure'. Rutgers University Press: New Brunswick, NJ.
10. Matthews MR (ed.) (2014). 'International Handbook of Research in History, Philosophy, and Science Teaching'. Springer: Dordrecht, Netherlands.
11. Lederman NG (2006). In Flick LB & Lederman NG (eds.) 2006. op. cit, 301-317. 'Syntax of Nature of Science within Inquiry and Science Instruction'. Springer: Dordrecht, Netherlands.

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