NATURE OF SCIENCE

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Understanding nature of science is, now, widely perceived to be a vital learning outcome of science education. In this article, we briefly discuss the rationale for introducing 'nature of science' in school science curricula, its evolving perspectives, and the approaches we may adopt to enable the learning of this topic.

Introduction

What is science? It is not uncommon for textbooks of science to begin with this question in the introductory chapter, devote a few paragraphs to it, and then get on quickly with what is regarded as the main stuff of science: its empirical facts, laws, theories, etc. Typically, the books would say: science involves 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 the empirical laws, which then lead us to build elaborate theories to explain the 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 nature of science, simplistic though it will seem as we discuss it further. But first, we must ask why it is necessary at all to teach nature of science when there is so little time to finish the 'more important' parts of the subject.

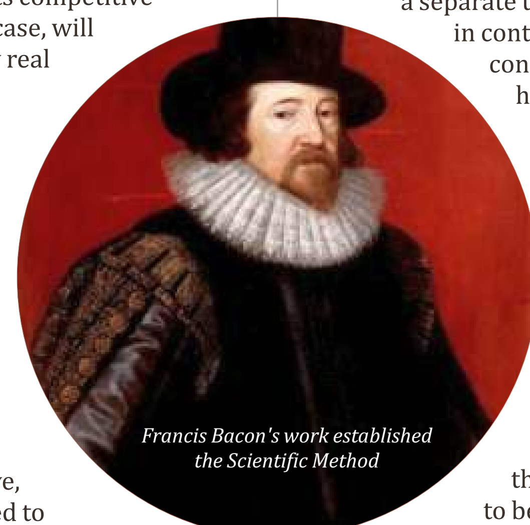
Why teach 'Nature of Science' (NOS)

To respond to this question, we must pause to reflect on what is the purpose of teaching science in school. Science is a compulsory subject in the Indian school curriculum till the end of secondary school. A majority of students will cease to go for further formal education; of those who do pursue higher stages of education, many would go to commerce, arts and other streams. Therefore, only a small fraction of students finishing Class X will choose to continue in the science stream, and a still smaller fraction of this number will go on to become scientists or other professionals who directly need science and its applications in their careers. Thus most people are unlikely to need any scientific content knowledge (of the kind learnt at school) in their professions.

Why, then, have we made science education compulsory at the school level? Clearly, this would make sense only if the main purpose of school science education was somewhat broad and not limited to specific science content only. The goals of school science education have been debated endlessly, often with differing ideological stances; but few would disagree that a principal goal is to generate an informed science citizenry in the country. Students need to grow into citizens who have a feel for what science is about, what methods and processes are involved in generating new science, and what relation science has with technology and society. This has become increasingly necessary, because science and technology are deeply impacting our ways of living. Citizens need to have some minimal familiarity with modern technology, its possible benefits and risks; its impact on our health and environment, etc.; so that they can make informed choices, and formulate mature opinions about these issues. Science, some would argue, has ushered in the Age of Reason, and can help encourage a rational outlook about life (though at present this seems like a distant goal!). These, and several other allied objectives, are sometimes, clubbed under the head 'science and technology literacy'. There are numerous variants of this term, and many shades and nuances, but, perhaps, it is safe to say that the rationale for teaching NOS is tied closely to this general goal of school science education.

Does that mean 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 our future scientists? Will our country not lose out on its competitive edge in science? And, in any case, will the teaching of NOS be of any real use for the larger majority of students we have in mind?

These concerns, widely shared among teachers (and scientists), arise naturally because the relevance of NOS in the school science curriculum, and its pedagogy, are still not very clear. First, it is not correct to think that NOS is relevant only for the non-science group indicated above, and that future scientists need to focus only on acquiring conceptual knowledge that is at the core of their subject. On the contrary, there is an increasing feeling among educators that learning NOS can deepen one's understanding of the subject itself. For the past few decades, science education researchers have carried out detailed studies at different levels, on the epistemic and ontological beliefs of students with regard to their subject,


Francis Bacon's work established the Scientific Method

> By epistemic beliefs we mean our ideas on how scientific knowledge is generated and justified; by ontological beliefs we mean broadly our ideas on the basic categories of objects that exist in nature. For example, classical physics regards particles and electromagnetic waves as two distinct ontological categories, a distinction that gets blurred in modern physics.

and have concluded that these could have a bearing on their critical understanding of the content of the subject.

In short, understanding nature of science is not only relevant for the general goal of promoting science and technology literacy; it is just as relevant to a science student, in developing a deeper appreciation for her subject.

Second, what is envisaged is not to 'dilute' the content of science, but rather to use it imaginatively, as a means to teach NOS, among other things. In other words, NOS is to be taught, not by preaching abstract generalities set aside in a separate unit of the book; it is to be put in context by interleaving it with the content of science. Before we see how that might be done, we must first broadly agree on what our views are on 'nature of science'.

Nature of science: evolving perspectives

The nature of science has been a subject of philosophical inquiry all through history, and continues to be so, even now. As science has advanced, particularly in the last four centuries, so have our ideas about the nature of science. When, in the 16th and 17th centuries, modern science was being shaped by the work of Galileo, Descartes, Kepler and Newton; Francis Bacon was formulating, what we now call, the scientific method. Roughly speaking, the introductory paragraph of this article replicates Bacon's ideas of nature of science. The essence of Bacon's ideas is that science is inductive generalization from unbiased observations of nature, and controlled experiments. Bacon foresaw the immense power of this new method in not only predicting, but also controlling phenomena.

In the beginning of the 20th century, an influential group of philosophers of science undertook 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 in a verifiable form; science must only have such meaningful statements. For convenience, we may use theoretical terms like 'atom', 'gene', 'valency', but ultimately, all scientific assertions must be reducible to observation statements. By this strict criterion, poetry is meaningless, if harmless, while a metaphysical assertion is both meaningless and harmful, since it purports to be true! The proponents of this philosophy, called logical positivism (and in its later, more moderate, version, called logical empiricism), could not realise their ambition of translating all of science in these terms.

In the same spirit of analysing the scientific method, but distinct from logical positivism in many ways, was the philosophy of Karl Popper. Popper was driven by a desire to differentiate between science and, what he regarded as, pseudoscience. He is famous 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. If the prediction is verified, you have not confirmed the theory; you have simply not shown it to be false yet. This is precisely where pseudo-sciences differ—they do not give clear-cut testable predictions, and can accommodate any observation. 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 was inspired by Einstein's work, and his ideas usually resonate with scientists; he is often called the scientists' philosopher.

In an incisive criticism of these dominant ideas, around the 1950s, Quine argued that a scientific theory is a complex web of interconnected assumptions and claims that relate to experience as a whole. Consequently, it is not 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 of science, clearly separated the context of discovery (the intuitive creative phase of science embedded in particular social settings) from the context of justification (critical philosophical scrutiny of theories claimed to be correct). The former was thought to belong to the realm of psychology /sociology. This distinction kept the actual practice of science, largely, beyond their purview. In other words, the attempt was to formulate what the scientific method should be, rather than what it was actually.

Around 1960s, Thomas Kuhn's, now famous, book 'The Structure of Scientific Revolutions', marked the beginning of a major transformation of our ideas of nature of science, and how it progresses. Analyzing 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 up to a point, and do not abandon their existing theories even in the face of some anomalies (disagreement with experiment). However, when the anomalies are stark and accumulate with time, there is a crisis in normal science, and the existing paradigm is questioned. All kinds of alternative ideas float during the crisis, out of which some promising new ideas begin to attract consensus, often because of some particularly striking exemplars. A new paradigm is born, and normal science returns, in which scientists work out the details and applications of the changed paradigm.

The key point to note in Kuhn's philosophy is that the paradigm shift is not governed by a purely rational process; it involves a social consensus in the scientific community. The adherence to an existing paradigm in normal science is secured through training in our colleges and graduate schools. Not everybody agreed with Kuhn. Lakotos found the undermining of the rational basis of scientific progress implied in Kuhn's ideas unacceptable, and developed his own theory in terms of the notion of competing 'research programmes'. Feyerabend dismissed the very idea that there is any clear method in the way science evolves. His philosophy is often summarized by the catchy line: 'anything goes'. His noted book 'Against Method' celebrates creativity in science and advocates freedom of imagination. Thus while Lakotos found the disorder inherent in Kuhn's view of science alarming, Feyerebend criticized Kuhn for just the opposite reason-- for his orderly and mechanical view of scientific progress. Normal science had a very significant role in Kuhn's scheme, since it goes deep into an accepted paradigm, making it possible to discover anomalies that eventually result in changing the paradigm. Feyerebend, on the other hand, criticizes the routine mind-numbing activities of normal science, and asserts that science progresses through creative leaps of imagination that defy existing ideas.

Whatever the merits of Kuhn's theory, it was certainly responsible for introducing a sociological dimension to philosophy of science, in the second half of the 20th century. Indeed some sociologists viewed the standard philosophy of science as irrelevant, and asserted that we can understand nature of science only by a critical and detailed probing of the actual way in which scientists work. This development has taken the debate on nature of science in many different directions that we cannot adequately describe here. But, we certainly have a better perspective now on the socio-cultural norms that enable science to grow. For example, it seems clear that the formation of robust social institutions of science (Scientific Societies in Europe, such as the Royal Society) practising norms of open and democratic discussion, peer reviewing of research, and communal ownership of scientific laws, etc. was as crucial for the growth of science, as the ingenuity of individual scientists.

We can summarise some new insights on nature of science that have gradually emerged from these discourses. First, science is not just induction from observations and experimental data; it often involves imaginative and radical new ideas not necessarily suggested by them. For example, some of the most successful theories of science have arisen from general considerations of simplicity and symmetry, and a drive for unification. Second, though observations of nature are often the starting point, not all observations are neutral - they are 'theory-laden'; theories, implicitly or explicitly, guide us to where and what to experiment and observe (this does not necessarily undermine the objectivity of science).

Third, observations and experimental data underdetermine correct theory; several different theories can all be consistent with them. Fourth, science is not a purely cognitive endeavour; though it is certainly constrained by the empirical facts of nature, it also involves some social consensus among scientists and needs enabling socio-cultural norms and conditions for its growth. Fifth, science, technology and society (STS) are intertwined in complex ways, affecting and being affected by one another. A corollary of the last point is that we must be alert to the possible pitfalls in scientific practice and the harmful consequences of uncritical and unwise use of technology.

This brief overview is intended only to give a flavour of the subject; it admittedly does not capture the many subtle aspects of philosophy of science. See, for example, Godfrey-Smith (2003)[1] for a deeper treatment of this subject, and for references of the classic works mentioned above.

Nature of science: how and what to teach

With so much of the historical debate on nature of science continuing into the present, what is it that we wish students to learn about NOS in school education? Obviously, we cannot import the complex philosophical issues on the matter into our classrooms. There has been much reflection on this point, and the feeling is that despite the wide range of perspectives, there is a core of generally accepted new ideas in NOS that are learnable by young students. We recommend referring to the New Generation Science Standards NGSS (2013)[2] developed in the U.S.A. Of course, similar objectives have been advocated elsewhere; see, for example, Pumfrey (1991)[3], Osborne et al (2002)[4]; and also Taylor and Hunt (2014)[5]. For a much deeper perspective on the subject, see Erduran and Dagher (2014)[6]. We summarize, here, what in our view appears to be a broad consensus; more details on NOS objectives can be found in the references cited.

<u>Nature of Science Objectives (Summary)</u>

Students should appreciate that…

<u>Scope</u>

…Science seeks to describe and explain the physical world based on empirical evidence. Some domains may be beyond its scope.

<u>Methods</u>

…Science adopts a variety of approaches and methods; there is no one universal method of science.

Science does not involve induction only. 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 judgements, and not just logical deductions. Hence there can be disagreement.

<u>Social aspects</u>

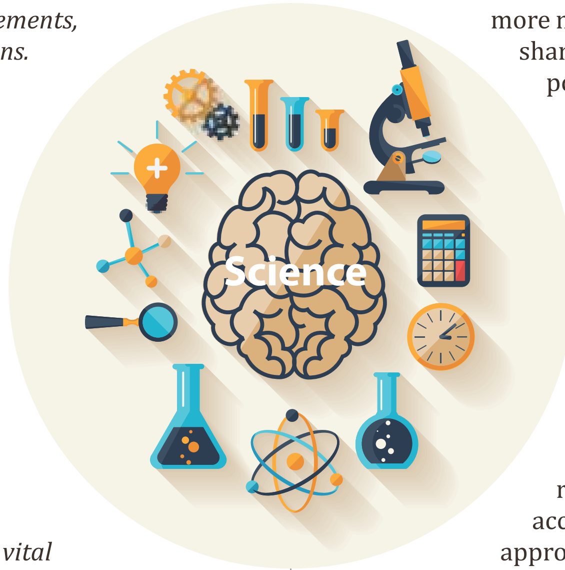
...Science is a co-operative multi-cultural human enterprise to which countless men and women contribute, including some noted individuals who play a significant role. Social institutions practising norms of open debate, peer reviewing and common ownership of knowledge are vital for its growth.

Science and technology may lead to issues that need socio-cultural resolution.

<u>Scientific knowledge</u>

...is dynamic and subject to revision by new empirical evidence.

Finally, the most important but difficult question: what pedagogy is to be employed to teach NOS? The idea that content alone is not enough in science education is not new, as the history of curriculum reforms since the 1960s (or even earlier) shows. Around the 1970s, some educational reforms emphasized processes of science more than its content: observing, measuring, classifying, analysing, inferring, interpreting, experimenting, predicting, communicating, etc. Soon there were critical appraisals of this approach; some educators questioned the very premise that there are a set of general transferable processes common to all sciences. See, for example, Millar and Driver (1987)[7]. For some time now, there seems to be a broad convergence on an Inquiry-based approach to science learning and teaching. This approach, informed by the constructivist philosophy, no doubt, involves learning the processes of science mentioned above; but it goes much further, to include posing questions, critical thinking, giving evidence-based explanation, justifying it, and connecting it to existing scientific knowledge, etc. Basically, this approach advocates the learning of science in a manner that resembles the way scientists carry out their investigations.



Inquiry tasks are naturally relatively simple for younger children, and quite elaborate for the more mature students, but they share the common feature of posing a question and seeking an evidence-based explanation. They can have different foci; some may relate to STS issues, while others may be more discipline-oriented. Inquiry may also include reflections on the inquiry mode itself, and thus naturally incorporate NOS educational objectives. We refer the reader to a critical account of the Inquiry approach, including its relation with NOS, in Flick and Lederman (2006)[8].

Another approach uses the History of Science (HOS) as a means to teach NOS. This again is not a new idea; see the excellent book by Holton and Brush (2001)[9]. Some key points in its favour are thought to be: HOS involves human narratives which enliven science and engage students' interest; it 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; and lastly, HOS is the most natural setting for learning NOS. We refer the reader to a comprehensive Handbook brought out recently on this issue (Matthews 2014)[10].

As Lederman (2006)[11] has forcefully argued, NOS objectives should be regarded as primarily cognitive outcomes that can be properly assessed. Instruction needs to bring them out explicitly, they are unlikely to be assimilated implicitly, whether we adopt an Inquiry or a History based approach. A whole range of inquiry tasks and HOS based vignettes, explicitly focussed on NOS; need to be developed if we aim to improve student understanding of nature of science.

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References

1. Introduction to Philosophy of Science. Godfrey-Smith P. (2003). Chicago. The University of Chicago Press.
2. Next generation science standards: For states, by states. NGSS (2013). Appendix H www.nextgenscience.org
3. History of science in the National Science Curriculum: a critical review of resources and their aims. Pumfrey, S. (1991). British Journal of the History of Science. 24, 61–78.
4. EPSE Project3 Teaching pupils 'ideas-about-science'. Osborne, J., Ratcliffe, M., Bartholomew, H., Collins, S. & Duschl, R. (2002b). School Science Review, 84 (307), 29–33.
5. History and Philosophy of Science and the Teaching of Science in England. Taylor J.L. and Hunt A. (2014). Matthews M.R. (ed.) op.cit. 2045-2082.
6. Reconceptualizing the Nature of Science for Science Education. Erduran S. & Dagher Z.R (2014). Dordrecht, Netherlands. Springer.
7. Beyond processes. Millar, R. & Driver, R. (1987). Studies in Science Education, (14) 33–62.
8. Scientific Inquiry and Nature of Science. Flick L.B. and Lederman N.G. (eds.) (2006). Dordrecht, Netherlands. Springer.
9. Physics, the Human Adventure. Holton G. and Brush S.G. 3rd ed. (2001). New Brunswick. NJ. Rutgers University Press.
10. International Handbook of Research in History, Philosophy and Science Teaching. Matthews M.R. (ed.) (2014). Dordrecht, Netherlands. Springer.
11. Syntax of Nature of Science within Inquiry and Science Instruction. Lederman N.G. (2006). In Flick L.B. and Lederman N.G. (eds.) (2006) op.cit, 301-317.

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Flatus: Beware!

Flatus is the gas generated in, or expelled from, the digestive tract, especially the stomach and intestines. More than 99% of human flatus comprises nitrogen, oxygen, hydrogen (hydrogen-consuming bacteria in the digestive tract may consume some of this to produce methane and other gases), carbon dioxide, and methane.

During World War II, US fighter pilots flew at increasing altitudes. The associated reduction in the (external) atmospheric pressure allowed the digestive gases trapped in their intestines to expand (Boyle's law), causing very painful cramps. Foods known for their ability to produce flatus – dried beans and peas, vegetables of the cabbage family, carbonated drinks, and beer – were therefore removed from pilots' menus.

Methane is a combustible gas (e.g. a good fuel for Bunsen burners), although it is produced by only about one-third of people in the Western world. In the early days of the space race, there was some concern that the methane emitted by astronauts, if accidentally ignited, could cause an explosion within the spacecraft. No such incidents have occurred to date. However, exploding flatus has caused the accidental death of at least one surgical patient. An electrode touched to the patient's colon ignited the hydrogen and methane it contained, also causing the surgeon to be blown back to the wall of the room.

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