Changing the Focus: From Nature of Science to Features of Science

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There has been a long tradition advocating the cultural, educational, personal and scientific benefits of infusing the history and philosophy of science, into science programmes and curriculum; or in current terms, of teaching about the nature of science (NOS) while teaching science. In the nineteenth century, the central figures were William Whewell (1854), Thomas Huxley (1885/1964) and Ernst Mach (1886/1986). In the early decades of the twentieth century John Dewey (1910, 1916) in the US and Fredrick Westaway (1919, 1929) in the UK were central figures. In the Anglo-American world, the tradition was continued by Joseph Schwab in the 1940s and 1950s (Schwab 1949, 1958); by Leo Klopfer (1969) and James Robinson (1968) in the 1960s; by Jim Rutherford (1972), Gerald Holton (1975, 1978), Robert Cohen (1975) and Michael Martin (1972, 1974) in the 1970s.[1]

In the past three decades a number of science educators have extended this tradition. Perhaps the most prominent have been Derek Hodson (1986, 1988, 2008, 2009), Richard Duschl (1985, 1990, 1994), and Michael Matthews (Matthews 1992, 1994, 1998, 2000, 2009). The International History, Philosophy and Science Teaching Group, through its conferences held biennially since 1989 and associated journal *Science & Education,* have contributed a great deal to this research tradition.

As well as advocacy there has been a mushrooming of empirical studies relating to NOS matters – determining NOS views held by scientists, teachers, and representative historians and philosophers; determining the optimal teacher and classroom conditions for most effective NOS teaching; ascertaining the connections between learning NOS and learning science content; developing valid, reliable and efficient tests to measure NOS learning; and so on. Here the work of Norman Lederman and his students have had a particular impact.[2]

Science is a human and thus historically-embedded truth-seeking enterprise that has many features: cognitive, social, commercial, cultural, political, structural, ethical, psychological etc. All of these features are worthy of study by science students as well as by disciplinary specialists; and different of them come into clearer focus when considering different sciences, and when considering different aspects of the history, achievements and practice of the different sciences. Some of the features are shared to a large degree with other knowledge-acquiring enterprises, some are shared to a limited degree, and some are not shared at all. Given these characteristics of science, it is useful to understand NOS not as some list of necessary and sufficient conditions for a practice to be scientific, but rather as something that, following Wittgenstein's terminology, identifies a 'family resemblance' of features that warrant different enterprises being called scientific.[3]

This essay will recommend a change of terminology and research focus from the essentialist and epistemologically focussed 'Nature of Science' (NOS) to a more relaxed, contextual and heterogeneous 'Features of Science' (FOS). Such a change of terminology

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[1] I have surveyed and commented on this history in Matthews (1994, chaps.4,5).
[2] See Lederman (1986, 1992, 2004, 2007), and contributions to Flick & Lederman (2004).
[3] This point has been persuasively argued by Gürol Irzik and Robert Nola (Irzik & Nola 2011).

and focus avoids the following philosophical and educational pitfalls that have been associated with a good deal of recent NOS research:

(1) The confused jumbling together of epistemological, sociological, psychological, ethical, commercial and philosophical features into a single NOS list.

(2) The privileging of one side of what are contentious and much-debated arguments about the methodology or 'nature' of science.

(3) The assumption of particular solutions of the demarcation dispute.

(4) The assumption that NOS learning can be judged and assessed by students' capacity to identify some number of declarative statements about NOS.

William Whewell: A Precursor to Contemporary NOS Debates

In 1854 the formidable English scientist, philosopher, historian, theologian and moralist William Whewell, gave a lecture in Leeds to the Royal Institution of Great Britain on the topic of 'On the Influence of the History of Science upon Intellectual Education' (Whewell 1854). He prepared the ground for his particular argument by saying:

> As the best sciences which the ancient world framed supplied the best elements of intellectual education up to modern times; so the grand step by which, in modern times, science has sprung up into a magnitude and majesty far superior to her ancient dimensions, should exercise its influence upon modern education, and contribute its proper result to modern intellectual culture. (Whewell 1854, p.242)

In the lecture he provided passionate argument for the inclusion of NOS (now called) into all liberal education, saying:

> …in the History of Science we see the infinite variety of nature; of mental, no less than bodily nature; of the intellectual as well as of the sensible world. …the history of science …*may* do, and carefully studied, *must* do, much to promote that due apprehension and appreciation of inductive discovery; and inductive discovery, now that the process has been going on with immense vigour in the nations of Europe for the last three hundred years, ought, we venture to say, to form a distinct and prominent part of the intellectual education of the youth of those nations. (Whewell 1854, pp.248-249).

Whewell believed that the history of science was indispensible for understanding 'intellectual culture' more generally, by which he meant the processes of knowledge creation or epistemology. One hundred and more years before Karl Popper, Imre Lakatos and Thomas Kuhn made the view popular, Whewell argued that philosophy of science has to be informed by history of science. In Lakatos's words:

> Philosophy of science without history of science is empty; history of science without philosophy of science is blind. (Lakatos 1978, p.102)

Whewell's point is worth drawing attention to, as so much NOS discussion in science education goes on in direct violation of it. NOS is frequently taught without reference to history, and is not informed by history. Unfortunately teachers wishing to convey something of NOS do so by having students 'reflect on', 'brainstorm', or 'discuss' their own classroom activities or investigations as if this was the window onto science.

It was from this conviction that Whewell's monumental 3-volume *History of the Inductive Sciences* (Whewell 1837) informed his equally monumental *Philosophy of the*

Inductive Sciences, Founded upon Their History (Whewell 1840).[4] A source of some confusion is that, despite the title of his books, Whewell was not an inductivist; he did not think that the history of science displayed an inductive/empiricist methodology as currently understood. On the contrary as he famously said in his *History* 'There is a mask of theory over the whole face of Nature'. It was from such a 'theory first' or hypothetico-deductive position that in 1849 he criticized John Stuart Mill's hugely popular and influential *A System of Logic* (Mill 1843) that had been published a few years earlier and after his own two treatises (Whewell 1849).[5]

Whewell also expressed two concerns that have occupied much contemporary NOS research when he went on to ask:

> How is such a culture to be effected? And also, how are we to judge whether it has been effected? (Whewell 1854, p.249)

Whewell was, in contemporary terms, asking: How can NOS best be taught? and, How can NOS learning best be assessed? Educators and researchers are still asking and answering these questions.

NOS in Contemporary Curricula

Contemporary educational concern with teaching NOS (broadly construed) can be dated from the 1980s and can be seen in numerous US, UK, Canadian, Turkish, Greek and other national and provincial government reports and curricula (McComas & Olson 1998). This concern with NOS is perhaps most clearly seen in affirmations of the American Association for the Advancement of Science, especially its landmark 1989 publication *Science for All Americans* (AAAS 1989) and its 1990 *The Liberal Art of Science* (AAAS 1990). The latter stated that:

> The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues. (AAAS 1990, p.xiv)

This was elaborated in their *Benchmarks for Science Literacy* document (AAAS 1993). The AAAS believes that learning about science – its history and methodology - will have a positive impact on the thinking of individuals and will consequently enrich society and culture. That is, NOS learning will have a flow-on effect outside the science classroom. This was, as we will see, an essential belief that the Enlightenment philosophers and educators held about instruction in science or 'natural philosophy'.

The expectations of the AAAS found their way through to the *US National Science Education Standards* which were drawn up by the National Research Council (whose members were drawn from the councils of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine). The *Standards* have a separate content strand devoted to 'History and Nature of Science Standards' (NRC 1996).

In the United Kingdom there has been a longer tradition of recognising the importance of NOS learning, broadly construed, in science teaching. Fredrick Westaway, an 'Her Majesty's Inspector of Schools' in the UK in the 1920s who also authored substantial

[4] An accessible source for some of Whewell's historical and philosophical studies is Elkana (1984). This includes selections from his *Bridgewater Treatises* on natural theology.

[5] On this, see Elkana (1984, chap.xxii), Laudan (1981), and Yeo (1993).

books on history of science and philosophy of science, wrote that a successful science teacher is one who:

> knows his own subject . . . is widely read in other branches of science . . . knows how to teach . . . is able to express himself lucidly . . . is skilful in manipulation . . . is resourceful both at the demonstration table and in the laboratory . . . is a logician to his finger-tips . . . is something of a philosopher . . . is so far an historian that he can sit down with a crowd of [students] and talk to them about the personal equations, the lives, and the work of such geniuses as Galileo, Newton, Faraday and Darwin. More than this he is an enthusiast, full of faith in his own particular work. (Westaway 1929, p.3)

The most recent concerted UK effort to teach NOS material is the new optional Upper Level *Perspectives on Science* course for England and Wales (Swinbank & Taylor 2007). The course has four parts:

Pt.1 Researching the history of science
Pt.2 Discussing ethical issues in science
Pt.3 Thinking philosophically about science
Pt.4 Carrying out a research project

The textbook for this course, on its opening page, says:

> *Perspectives on Science* is designed to help you address historical, ethical and philosophical questions relating to science. It won't provide easy answers, but it will help you to develop skills of research and argument, to analyse what other people say and write, to clarify your own thinking and to make a case for your own point of view. (Swinbank & Taylor 2007, p.vii)

The Philosophy section begins with about 16 pages outlining fairly standard matters in philosophy of science – nature of science, induction, falsifiablity, paradigms, revolutions, truth, realism, relativism, etc. Importantly, the book then introduces the subject of 'Growing your own philosophy of science' by saying:

> Having learned something about some of the central ideas and questions within the philosophy of science, you are now in a position to evaluate the viewpoints of some scientists who were asked to describe how they viewed science. The aim here is to use these ideas as a springboard to develop and support your own thinking. (Swinbank & Taylor 2007, p.149)

The Enlightenment Tradition

To better understand reasons for contemporary advocacy of history and philosophy, or NOS, in science teaching, and current concern to have empirical studies of the efficacy of teaching NOS, it is informative to go back to the origins of these concerns in the European Enlightenment.[6] The Enlightenment philosophers - Locke, Voltaire, D'Alembert, Condorcet, Hume; and a little later Franklin, Priestley, Jefferson and Kant - were inspired by the dramatic achievements of the New Science of the seventeenth century. The seventeenth-century Scientific Revolution was the seed that produced the eighteenth-century Enlightenment plant. The scientific accomplishments in mechanics, astronomy, horology,

[6] Some excellent recent books on the Enlightenment include Dupré (2004), Hankins (1985), Himmelfarb (2004), Israel (2001) and Porter (2000).

medicine and other fields are well known. These 'natural philosophy' endeavours were institutionalised with the establishment of The Royal Society in England (1660) and the *Académie Royal des Sciences* in France (1666).[7]

David Hume, in his *History of England*, wrote that Newton was 'the greatest and rarest genius that ever rose for the ornament and instruction of the species' (Hume 1754-62/1828, Vol. IV, p.434). This was of course one Englishman writing about another Englishman, but nevertheless Hume well expressed the general view of Newton's preeminence in seventeenth-century science. Newton famously said in a letter to Robert Hooke (5th February 1676), 'If I have seen a little further it is by standing on the shoulders of Giants'. Although Newton did so stand, and there were many giants to stand on, including Galileo, Kepler and Huygens, clearly his *Principia* (Newton 1713/1934) and *Optics* (Newton 1730/1979) provided the foundation of modern science and the inspiration for the Enlightenment. Newton's self-styled 'under-labourer', John Locke, wrote five major Enlightenment texts in the decade after the publication of the *Principia* (Locke 1689/1924, 1689/1983, 1690/1960, 1693/1996, and 1695/1999).

In the appalling, unhealthy, warring, oppressive, autocratic, social, political, religious and cultural circumstances of seventeenth-century Europe - with its witch crazes, religious wars, heretic burnings, divine-right lords, denial of all free speech, and so on - it was not surprising that many thought that it would be truly wonderful if Newton's scientific achievements might be replicated in fields outside of natural philosophy; if his approach and 'method' could be applied more broadly. It was the hope of many that lessons from the New Science might have flow-on effects for culture, society and personal life. Newton certainly had this view. As he stated it: 'If natural philosophy in all its Parts, by pursuing this Method, shall at length be perfected, the Bounds of Moral Philosophy will be also enlarged' (Newton 1730/1979, p.405).

The Enlightenment philosophers held three convictions:

(1) They believed that the method of the new science was the only way of finding out truths about Nature; the methods of the Scholastic natural philosophers were obsolete and of no use.
(2) They thought that the new method had application well beyond the observatory, laboratory and workbench; the new method was useful in the investigation of many social, cultural and even religious questions.
(3) They thought that the method of the new science was not something just to be utilised by the natural philosophers, the scholars or the learned elite. They were committed to education, and the promotion of 'scientific' thinking in the population; they believed in, as one might say, 'Science for All'.

John Dewey, three hundred years later, well expressed these Enlightenment hopes when he said:

> Scientific method is not just a method which it has been found profitable to pursue in this or that abstruse subject for purely technical reasons. It represents the only method of thinking that has proved fruitful in any subject. (Dewey 1910, p. 127)

And when, in his justly famous *Democracy and Education*, he wrote:

> Our predilection for premature acceptance and assertion, our aversion to suspended judgment, are signs that we tend naturally to cut short the process of testing. We are satisfied with superficial and immediate short-visioned applications. ... Science represents the safeguard of

7 One of numerous guides to the achievements of the Scientific Revolution is Gribbin (2002, Book 2).

> the race against these natural propensities and the evils which flow from them. ... It is artificial (an acquired art), not spontaneous; learned, not native. To this fact is due the unique, the invaluable place of science in education. (Dewey 1916, p. 189)

Some Problems with Contemporary Empirical NOS Research: The Lederman Programme

Many individuals and groups in science education have researched factors impinging on the teaching and learning of NOS: What is taught? How it is taught? What is learned? How it is best learnt? What are the different outcomes between explicit or implicit instruction? etc.[8] This research has achieved much, but suffers because of 'soft focus' and ambiguous writing at critical points where important philosophical issues are at play. The field of NOS research in science education is yet another example where more cooperation between science educators, historians and philosophers would considerably improve the usefulness and quality of published work.

At the outset it is important to appreciate that science educators have typically taken a broad, and fairly relaxed, view of the nature of science; this 'relaxed' position bears upon the validity of test instruments and of informed assessment of NOS learning.[9] In many cases what are labelled 'NOS factors' by test designers and education researchers would be thought of as just 'features of science' by philosophers; not necessarily things that especially distinguish science or, in essentialist terms, pertain to the nature or essence of science.

This section will deal with the work of just one representative group of science education researchers, the group that formed around Norman Lederman.[10] This group is chosen because they have been working for two decades or so, and probably are the most cited and the most influential authors in the field. Their definition of NOS is characteristically catholic:

> Typically, NOS refers to the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development. (Lederman et al. 2002, p.498)

It is noteworthy that in this definition both epistemological *and* sociological aspects of science are subsumed under the NOS umbrella. This rings philosophical alarm bells; it should alone be sufficient to suggest a change from 'nature of science' to 'features of science'. There may well be some limits on the epistemology or methodology of science, but clearly there will be no such limits on the sociology of science; the latter will cover politics, commerce, education, professional structures, advertising, and whatever else those studying science as a historical process might have an interest in.

The 'Lederman Seven'

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[8] See contributions to special issues of *Science & Education* (vol.6 no.4 1997, vol.7 no.6 1998), McComas (1998), Flick and Lederman (2004) . See also the literature reviews in Abd-El-Khalick & Lederman (2000) and Lederman (2007).

[9] For a critical account of instruments used for NOS assessment from the 1950s to the present, see Lederman, Wade and Bell (1998).

[10] Norman Lederman, now professor of science education at the Chicago Institute of Technology, was formerly at Oregon State University. Among his many publications see especially Lederman (1992, 2004). His original Oregon State students included Fouad Abd-El-Khalick, Renee Schwartz, Valarie Akerson and Randy Bell - all of whom have published widely in this field.

The Lederman group maintains that 'no consensus presently exists among philosophers of science, historians of science, scientists, and science educators on a specific definition for NOS' (Lederman 2004, p.303). Although recognising no across-the-board consensus on NOS, the group does claim that there is sufficient consensus on central matters for the purposes of NOS instruction in K-12 classes. The group has elaborated and defended seven elements of NOS (the 'Lederman Seven' as they might be called) that they believe fulfil the criteria of:
(i) accessibility to school students;
(ii) wide enough agreement among historians and philosophers; and
(iii) being useful for citizens to know.[11]

The seven elements are:

1. The *empirical nature of science*, where they recognised that although empirical, scientists do not have direct access to most natural phenomena. It is claimed that 'Students should be able to distinguish between observation and inference … An understanding of the crucial distinction between observation and inference is a precursor to making sense of a multitude of inferential and theoretical entities and terms that inhabit the worlds of science' (Lederman et al. 2002, p.500).

2. *Scientific theories and laws*, where they hold that 'laws are descriptive statements of relationships among observable phenomena… Theories by contrast are inferred explanations for observed phenomena or regularities in those phenomena. … Theories and laws are different kinds of knowledge and one does not become the other.'(Lederman et al. 2002, p.500)

3. The *creative and imaginative nature of scientific knowledge*, where they hold that 'science is empirical … Nonetheless, generating scientific knowledge also involves human imagination and creativity. Science … is not a lifeless, entirely rational and orderly activity. …scientific entities, such as atoms and species are functional theoretical models rather than copies of reality.' (Lederman et al. 2002, p.500)

4. The *theory-laden nature of scientific knowledge*, where it is held that 'Scientists' theoretical and disciplinary commitments, beliefs, prior knowledge, training, experiences, and expectations actually influence their work. All these background factors form a mindset that affects the problems scientists investigate and how they conduct their investigations.' (Lederman et al. 2002, p.501)

5. The *social and cultural embeddedness of scientific knowledge*, where it is held that 'Science as a human enterprise is practiced in the context of a larger culture and its practitioners are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded.' (Lederman et al. 2002, p.501)

6. The *myth of scientific method*, where it is held that 'There is no single scientific method that would guarantee the development of infallible knowledge.. and no single sequence of

[11] The list is articulated and defended in, among other places, Lederman et al. (2002, 499-502), Lederman (2004, 303-308), Schwartz and Lederman (2008, 745-762).

activities .. that will unerringly lead [scientists] to functional or valid solutions or answers.' ((Lederman et al. 2002, p.502)

7 The *tentative nature of scientific knowledge*, where it is maintained that 'Scientific knowledge, although reliable and durable, is never absolute or certain. This knowledge, including facts, theories, and laws, is subject to change.' (Lederman et al. 2002, p.502)

This list has functioned widely in science education as a NOS checklist; it appears on classroom walls somewhat like the Seven NOS Commandments; and it informs the group's hugely popular series of VNOS (Views of Nature of Science) tests which are used in scores of published research papers to measure effectiveness of NOS teaching (Lederman et al. 2001) and degrees of NOS understanding (Flick & Lederman 2004, chap.IV, Schwartz & Lederman 2008, Chen 2006). The positive side of the list is that it puts NOS into classrooms; it provides researchers with an instrument for measurement of NOS learning; and it can give teachers and students some NOS matters to think through and become more knowledgeable about. The negative side is that the list can, despite the wishes of its creators, function as a mantra, as a catechism, as yet another something to be learn. Instead of teachers and students reading, analysing, and coming to their own views about NOS matters, the list often short-circuits all of this. And in as much as it does so, it is directly antithetical to the very goals of thoughtfulness and critical thinking that most consider the reason for having NOS (or HPS) in the curriculum.

As an example of the hurdles that attend an NOS focus, consider the much-written on claim made by the philosopher Larry Laudan that it is impossible to even demarcate science from other intellectual pursuits. Laudan maintains that:

> From Plato to Popper, philosophers have sought to identify those epistemic features which mark off science from other sorts of beliefs and activity. Nonetheless, it seems pretty clear that philosophy has largely failed to deliver the relevant goods. Whatever the specific strengths and deficiencies of the numerous well-known efforts at demarcation . . . it is probably fair to say that there is no demarcation line between science and non-science, or between science and pseudo-science, which would win assent from a majority of philosophers. (Laudan 1996, p.210)

If Laudan is correct, then the whole prospect of identifying, much less, itemising some NOS list is otiose.[12] But a focus on FOS avoids this hurdle. The possibility of demarcation is just one of numerous features of science that can engage teachers and students. The demarcation question becomes a subject for inquiry, not a catechismal matter. An FOS focus leaves open the demarcation question; a NOS focus presupposes a particular answer to it.

The Devil is in the Detail: The Need for Philosophical Articulation

The seven features of science, or NOS elements, clearly need to be much more philosophically and historically refined and developed in order to be useful to teachers and students. This is not just the obvious point that when seven matters of considerable philosophical subtlety, and with long traditions of debate behind them, are dealt with in a few pages, then they will need to be further elaborated, rather it is the more serious claim that at

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[12] Laudan first made the claim in his 'Demise of the Demarcation Problem' (Laudan 1983). A recent survey of the ensuing debate, and refutation of the claim, is provided by Robert Pennock (2011).

crucial points there is ambiguity that mitigates the list's usefulness as curricular objectives, assessment criteria, and as goals of science teacher education courses.

For instance consider the first item on the list – the empirical basis of science. There are two large problems that this label glosses over: First, the ontological status of theoretical entities in science; second, the role of abstraction and idealisation in science.

First, in discussing the empirical nature of science, it is maintained that there is wide enough agreement on the 'existence of an objective reality, for example, as compared to phenomenal realities' (Lederman 2004, p.303). This is quite so, but the serious debate among philosophers is not the reality of the world, but the reality of explanatory entities proposed in scientific theories. This debate between realists on the one hand, and empiricists, constructivists and instrumentalists on the other has gone on since Aristotle's time.

Aristotle maintained that the crystalline spheres in which the planets were supposedly embedded were a real existing mechanism that kept planets in their regular circular orbits, his empiricist rivals held that the spheres were merely mental connivances to give order to experience, they had no ontological reality. The debate was famously replayed when Cardinal Bellarmine urged Galileo to adopt an instrumentalist view of Copernican heliocentric astronomy – that heliocentrism was useful for astronomical calculations, but it was not actually how the solar system was arranged.[13]

The debate replayed when Bishop Berkeley criticised Newton's realist account of force, saying that: 'Force, gravity, attraction and similar terms are convenient for purposes of reasoning and for computations of motion and of moving bodies, but not for the understanding of the nature of motion itself' (Berkeley 1721/1901, p.506).[14] And it played again when the positivist Ernst Mach criticised realist interpretations of atomic theory, saying that those theorists had 'done more than science, whose aim is facts, requires of him – and this work of superogation is an evil' (Mach 1872/1911, p.57).

The debate between realist and empiricist or instrumentalist interpretations of the theoretical entities postulated by scientific theories was central to disputes in quantum mechanics (Bunge 2003). And has recently surfaced in Chemistry over the reality or otherwise of chemical bonds: Are there really covalent and ionic bonds or is there just macro-bonding behaviours for which postulation of micro unseen bonds is just a convenient shorthand for regularities at the macro level? (Vollmer 2003). [15]

Throughout the 2,500 years since Aristotle's postulation of crystalline spheres, it has not been the existence of the world that has been doubted – Bellarmine, Berkeley, Mach, and Bohr did not doubt the existence of objects, just the unseen entities and mechanisms that the science of their time was postulating to explain the visible, macro or phenomenal behaviour of the objects. This whole history is removed from science education discussion when the first element in the Lederman list simply says that 'science has an empirical base'. Well yes, it does, but the issue is more complex; and as with many things, the devil is in the detail. It might be said that students cannot comprehend the detail, but this is an empirical matter; certainly teachers can and should comprehend the detail.

The Lederman group are realists about the world, but it is very unclear whether they are realists about science's theoretical entities – the very issue on which the realist/instrumentalist (constructivist) debate has hinged. It is not the reality of the world that teachers need guidance about, it is the reality or otherwise of entities postulated in scientific theories. Lederman rhetorically asks: 'can it be said that a student truly understands the concept of a gene if he/she does not realize that a "gene" is a construct invented to explain

[13] The classic treatment of the ancient and medieval debates about 'saving appearances' as the goal of natural philosophy is Duhem (1908/1969).

[14] For Berkeley's positivist critique of Newtonian theory, see Popper (1953/1963).

[15] For the outlines of this debate, and a guide to some of the literature, see Matthews (1994, chap.8).

experimental results?' (Lederman 2004, p.314) And repeats the question by asking: 'Does the student who views genes as possessing physical existence analogous to pearls on a necklace possess an in-depth understanding of the concept?' (ibid) The point is repeated when it is asked: 'Does the student who is unaware that the atom (as pictured in books) is a scientific model used to explain the behavior of matter and that it has not been directly observed have an in-depth understanding of the atom? (ibid.)

These questions mask serious and misleading ambiguity concerning the existence of genes and atoms. At first reading, the questions seem to suggest an instrumentalist, non-realist view of these central explanatory entities; they appear to 'in principle' not exist, but be merely a human 'construct'. What if the student thinks of genes not as pearls on a necklace, but links in a necklace chain: Is this sufficient sophistication to rate as high NOS understanding? Or what if a student thinks of atoms not as pictured in the textbook, but as some sort of micro particle: Is this sufficient to rate as high NOS understanding? The crucial NOS issue is whether genes and atoms exist at all, exist in principle, not whether any particular picture of them is correct. Once we grant in-principle existence, we can be reasonably relaxed about any particular picture; this is just a matter for good science education to fill in. But Lederman is silent about whether it is in-principle existence or just some particular existence – pearl-like genes, or red and green atoms – that is being denied.

The same ambiguity can be seen when another member of the group, Fouad Abd-El-Khalick, recognises that 'The world of science is inhabited by a multitude of theoretical entities, such as atoms, photons, magnetic fields, and gravitational forces to name only a few.' All realists recognise that the entities listed are both theoretical and central to science, but Abd-El-Khalick proceeds to say that these are 'functional theoretical models rather than faithful copies of "reality"' (Abd-El-Khalick 2004, pp.409, 410). Here again is the crucial ambiguity. One wonders why 'reality' was put in scare quotes as this introduces some element of doubt about reality itself, but this doubt can be left aside for the moment as he is a realist about reality. But more importantly, functional theoretical models can either have a reference (denote something existing) or merely link observables in a, usually, mathematical way that has no ontological import. Abd-El-Khalick's claim is ambiguous at the crucial point of whether the listed theoretical entities are non-existing 'functional theoretical models' in virtue of them not being 'faithful copies of reality' or in virtue of their very nature.

This is a re-phrasing of the long discussed distinction between hypothetical constructs (which in principle can have existence, although they may, as a matter of fact not exist; or not exist with the properties attributed to them) and intervening variables (which in principle have no existence, but merely link observables).[16] In the nineteenth century, caloric and Neptune were hypothetical constructs; one turned out to have existence, the other did not. The notion of 'average-family number' when applied to societies functions as an intervening variable: there is no suggestion that any particular family has 3.7 members; the latter is not meant to copy, faithfully or otherwise, any particular reality. The crucial question is whether atoms, photons, magnetic fields, gravitational forces are like average-family numbers? Bellarmine, Berkeley, Mach and Bohr would say 'yes'; it is simply unclear if Abd-El-Khalick agrees with them or not. If attention had been paid to spelling out the meaning of 'functional theoretical model' this ambiguity would be removed.

At a surface reading, it would seem that the Lederman group are empiricists and constructivists about theoretical entities in science. If so, this is a mistake, and is not the

[16] A classic discussion of the difference between hypothetical constructs (that in principle have existence) and intervening variables (that in principle do not have existence) is Meehl and MacCorquodale (1948). Clarity on this issue is of absolute importance in social science: Is 'intelligence' to be understood as a hypothetical construct or an intervening variable? Rivers of ink have been spilt because researchers have not clarified the kind of thing they are looking for.

message about NOS that science teachers should convey. The mistake is not so much the assumption of one philosophical side, constructivism, in this debate but rather giving the impression that there is no debate or no alternative position that can and has been adopted – the realist position. Once again, a concentration on *the* NOS rather than open discussion and inquiry about FOS leads to this mistake.

The second problem with the Lederman Group's 'empirical basis' characterisation is that it disguises, if not completely distorts, the non-empirical component of science. The very process of abstraction, and idealisation, is the beginning of modern science. It is an ability to see the forest, and not just the trees. Consider Galileo's 'thousands of swings' of the pendulum. He clearly saw no such thing, it is a claim about what he would see if the impediments to pendulum motion were removed (Matthews 2000). Similarly Newton did not see inertial bodies continuing to move in a straight line indefinitely. This is what he would have seen if all resistance were removed. Fermi and Bernardini, in their biography of Galileo, emphasise this innovation:

> In formulating the 'Law of Inertia' the abstraction consisted of imagining the motion of a body on which no force was acting and which, in particular, would be free of any sort of friction. This abstraction was not easy, because it was friction itself that for thousands of years had kept hidden the simplicity and validity of the laws of motion. In other words, friction is an essential element in all human experience; our intuition is dominated by friction; men can move around because of friction; because of friction they can grasp objects with their hands, they can weave fabrics, build cars, houses, etc. To see the essence of motion beyond the complications of friction indeed required a great insight. (Fermi & Bernardini 1961, p. 116)

The point of this drawn-out discussion of the first item on the Lederman list is to indicate that such a claim about the empirical basis, and the role of inference, needs to be elaborated at a much more sophisticated level in order to both be useful and to avoid massive misunderstandings of the scientific endeavour. Further with just the slightest elaboration, the more or less uncontroversial and mundane claim – that science has an empirical base – can be transformed into an engaging inquiry that can link teachers and students with a central philosophical argument in the history of philosophy, namely realist or instrumentalist interpretation of scientific theory, a debate to which the greatest minds can be found on either side. It is not a simple, 'open and shut' matter that can be reduced to a declarative list.

The same kind of argument can be mounted against each of the other items on the Lederman list. A general point is that such necessary elaboration depends upon teachers having some competence or at least familiarity with the history and philosophy of science, and notoriously such training is absent from teacher-education programmes.

For instance the fourth claim is that 'Scientific knowledge is subjective or theory-laden'. Again, the claim is ambiguous: one can say both 'yes' and 'no'. First to acknowledge that some claim is theory-laden is not equivalent to saying it is subjective in the usual psychological meaning of the term. But the meaning being used by the Lederman group is simply ambiguous. For instance Lederman says that 'I am not advocating that scientists be subjective' (Lederman 2004, p.306). Here 'subjective' must be the everyday psychological sense of the term. But previously we have been dealing with, what one might call, 'philosophical subjectivity', as it has been stated that subjectivity is equivalent to theory-ladeness, and that 'subjectivity is unavoidable' (ibid.). Clearly all science is theory-laden, as Lederman rightly points out; but if so, then scientists have to be subjective (as in philosophical subjectivity), whether it is advocated or not advocated. But this is entirely different from psychological subjectivity.

The entire history of modern science is an effort to take out, or minimise, the psychological subjectivity in measurement and explanation – beginning with the earliest use of measuring instruments in order to get inter-subjective agreement about weight, length, time etc. Galileo's creation of the pusiligium so as to be able to objectively measure pulse rate for medical diagnosis is one such example. The entirely subjective 'fast', 'medium', 'slow' was replaced by the length of a pendulum beating in time with the patient's pulse.[17] The force of the fourth claim trades entirely upon an ambiguity, which is unfortunate in something so widely used as a check-list of NOS understanding.

The fifth claim is that science is embedded in culture, that it 'affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded' (Lederman 2004, p.306). It is important that this be recognised, but again the devil is in the detail, and the detail is not provided. We know that the cultures of Nazism (Beyerchen 1977), Stalinism (Graham 1973, Birstein 2001), Islam (Hoodbhoy 1991), and Hinduism (Nanda 2003) to take just some examples, dramatically affected scientific investigation wherever they were powerful enough to do so. And of course the impact, for good and bad, of Christian culture, beliefs and authorities on science is well documented (Lindberg & Numbers 1986). Clearly indigenous sciences are affected by the worldviews and social structures in which they are practised.

All commentators on the European scientific revolution recognise that the blossoming of the New Science of Galileo, Huygens, Newton, Boyle etc was dependent on, though not caused by, social and cultural circumstances of seventeenth century Europe.[18] Counterwise, scholars have tried to identify the absence of such circumstances in China at the time to account for why there was no comparable scientific revolution in China (Needham & Ling 1954-65). In a famous and contentious study, Paul Forman attempted to provide a causal link between the culture of Weimar Germany and the creation of indeterminate quantum theory (Forman 1971).

The sociological and historical facts of the matter are not in dispute – science depends upon technology, mathematics, communications, money, education, philosophy and culture more broadly - and it is useful for students and teachers to be reminded of all this and to be given examples. But for this fact to be truly useful, and not just a sort of anthropological observation, teachers (and their pupils) need to be engaged in or inquire about issues such as: separating benign from adverse effects of culture; distinguishing good from bad science; identifying internal and external factors in scientific development; trying to determine just how analogous are Western and indigenous science; and so on. But the Lederman group is silent on these ultimately normative matters.

We are told just that although Western Science dominates North American schools, there 'exist other analogous sciences (e.g., indigenous science) in other parts of the world' (Lederman 2004, p.307). The ambiguity here over 'analogous' means that this item on the list gives no direction to teachers, either in cultures that are resistant to Western Science, or in multicultural situations. It is a too-easy step to move from this anthropological claim to the educational conclusion that where other analogous sciences exist, then they should be taught.[19] The group does say that NOS means, among other things, identifying the 'values and beliefs inherent to scientific knowledge and its development' (Lederman 2004, p.303). The use of the word 'inherent' suggests that effort will be made to spell out just what is and is not inherent to science, and this would be the occasion to comment on benign and adverse

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[17] See Matthews (2000, pp.88-89).

[18] The classic statement of this position, but with the causal twist, is Boris Hessen's 1931 *The Social and Economic Roots of Newton's 'Principia*'. For Hessen's text and commentary see Freudenthal & McLaughlin (2009). One well known elaboration of the thesis, in the causal direction, is Freudenthal (1986).

[19] For a philosophically sophisticated discussion of some of the issues, see Nola and Irzik (2006).

impacts of culture on science; but the matter is not addressed. This can be a good thing, if teachers and students are meant to work out their own answer, but the list is meant to function as a characterisation of the nature of science, and further is to be used in assessing competence in NOS understanding, for these purposes more elaboration is needed.

Item seven on the Lederman NOS list is a claim about the 'tentativeness' of scientific knowledge. We are told that 'tentativeness in science does not only arise from the fact that scientific knowledge is inferential, creative, and socially and culturally embedded' but 'There are also compelling logical arguments that lend credence to the notion of tentativeness in science' (Lederman 2004, p.307). Again, as with all the other items on the list, one can say 'yes' or 'no' depending on how the claim is interpreted. First, contrary to what is stated, absolutely nothing follows about tentativeness from the recognition that knowledge is 'inferential, creative, and socially and culturally embedded' unless one adds a premiss to the effect that, by definition, knowledge so characterised is tentative. But, without argument, there is no need to add such a premiss. If we infer a *particular* cause for some effect, this might be a tentative belief, but to infer that there is a cause, is not tentative in the same way.

Features of Science (FOS)

There are seven items on the Lederman NOS list:

(1) Empirical basis
(2) Scientific theories and laws
(3) Creativity
(4) Theory dependence
(5) Cultural embeddedness
(6) Scientific method
(7) Tentativeness

I have been arguing that these should better be thought of as different features of science (FOS) to be elaborated, discussed and inquired about, rather than nature of science (NOS) items to somehow be learnt and assessed. Each of these features has been richly written about by philosophers, historians and others – as has been indicated above for some on the list. But if they are features of science, then there is no good reason why just those seven features are picked out, and not others of the numerous features – epistemological, historical, psychological, social, technological, economic, etc - that can be said to characterise scientific endeavour, and that also meet the three criteria of accessibility, consensus and usefulness that the Lederman group additionally utilise to reduce NOS matters to classroom size.

Clearly many other things can be added to the above list. Among philosophers, NOS discussion and debate has traditionally revolved around investigations of the epistemological, methodological, and ontological commitments of science. But there are illuminating, non-philosophical studies of science, such as conducted by historians, cognitive psychologists, sociologists, economists, anthropologists, and numerous other disciplines. The term 'Science Studies' encompasses the complete academic spectrum, and all components have useful things to say about different features of science. Just some of the additional topics, issues or questions that can usefully engage science teachers and students might be:

(8) *Experimentation*. The long-standing Aristotelian injunction about not interfering with nature if we want to understand her was rejected first by Galileo, with his famous inclined plane experiments conducted so as to understand the phenomena of free fall, then

progressively by the other foundation figures of early modern science, most notably Newton with his pendulum experiments in mechanics and his prism manipulations in optics. It was this newly introduced experimentalism that occasioned Kant to remark that:

> When Galileo caused balls, the weights of which he had himself previously determined, to roll down an inclined plane; when Torricelli made the air carry a weight which he had calculated beforehand to be equal to that of a definite volume of water … a light broke upon all students of nature. They learned that reason has insight only into that which it produces after a plan of its own, and that it must not allow itself to be kept, as it were, in nature's leading-strings (Kant 1787/1933, p.20)

Historians and philosophers have written a great deal on this topic, and of course it can connect immediately with a more sophisticated understanding of school laboratory work and student experimentation (Chang 2010; Hodson 1993, 1996).

(9) *Idealisation*. What is the role, function and status of idealisation in scientific theorising? How are laws about idealised and contrary-to-fact conditions reconciled with claims that laws of nature are about the world? (Nowak 1980).

Galileo was the first to build idealisation into the investigation of nature, and it was this methodological move that enabled his New Science to emerge from its medieval and Renaissance milieu.[20] What Galileo recognised was that nature's laws were not obvious in nature; they were not given in immediate experience; the laws applied only to idealised circumstances. This employment of idealisation was also in flat contradiction to the long empiricist Aristotelian tradition whereby 'science' was to be about the world as seen and experienced. As Aristotle maintained: 'If we cannot believe our eyes what should be believe?' In contrast, Galileo immediately after proving his famous Law of Parabolic Motion, says:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola. (Galileo 1638/1954, p. 251)

Of crucial importance was the fact that idealisation, and only idealisation, gave specific direction to experimentation so that students of nature (reason) could mould nature 'after a plan of its own', in Kant's famous words. The decades and centuries of classical mechanics, began by Galileo, were a long process of transforming nature in the image of theory; that is what an experiment was: controlling all variables identified by theory as being irrelevant, and varying the one held responsible for the phenomena.

(10) *Models*. The ubiquity of models in the history and current practice of science is widely recognised, indeed it is difficult to think of science without models: the 'billiard ball', 'plum-pudding' and 'solar system' models of the atom, the electron orbit model for the periodic table, the 'lattice' model of salt structure, the fluid-flow model of electricity, the double-helix model of the chromosome, the 'survival of the fittest' model for population expansion in eco-systems, the particle model of light, the 'big bang' model in cosmology, the '3-body' model for sun-earth-moon interaction, full dinosaur models from bone fragments in palaeontology, the plate-tectonic model in geophysics, the scores of mathematical models in hereditary and population studies, the thousands of mathematical models in economics, engineering, and so

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[20] I have argued this claim at some length in Matthews (2000, pp.245-48).

on. Any ten pages of a science textbook might be expected to contain twice that number of models, many in full glossy colour, with state-of-the-art graphics.

In the past half-century historians and philosophers of science have devoted considerable time to documenting and understanding the role of models in science and social science. These studies have led scholars to examine model-related topics such as the nature of scientific theory, the status of hypothesis, the role of metaphor and analogy in scientific explanation, thought experiments in science, and the centrality of idealisation for the articulation, application and testing of models. Mary Hesse's (1953, 1961, 1966) and Rom Harré's (1960) publications were foundational for the contemporary tradition (realist and non-realist) of model-related research, with Hesse's *Models and Analogies in Science* (1966) being of particular importance. Philip Johnson-Laird's book *Mental Models* (1983) was, and still is, enormously influential. He, and associates, provided an explanation for the ubiquity of models in science when they detailed how models were ubiquitous not just in science but in all mental life.

Once more, if models are seen as an important feature of science, then a competent HPS-informed teacher can provide rich materials and questions for class discussion on the topic: How do models relate to the world they model? Is learning the properties of models the same as learning about the world?. As with so many FOS questions, there is no uncontested answer, just better informed and better argued answers. A number of rich studies can be seen in the recent special issue of *Science & Education* devoted to the subject - 'Models in Science and in Science Education' (2007, vol. 16 nos. (7-8).

And of course this extended FOS list can simply be extended to include any number of other important and engaging features of science:

(11) *Values and Socio-scientific issues*
(12) *Mathematisation*
(13) *Technology*
(14) *Explanation*
(15) *Worldviews and Religion*
(16) *Theory choice and rationality*
(17) *Feminism*
(18) *Realism and Constructivism*

All of these subjects have been extensively written upon, as can be seen by a perusal of any introductory HPS textbook.

Modest Goals for FOS Teaching

We should have modest goals when teaching about FOS. In the opening page of the AAAS *Benchmarks* document it was stated that: 'Little is gained by presenting these beliefs to students as dogma. For one thing, such beliefs are subtle' (AAAS 1993, p.5). The same points are made in the UK *Perspectives on Science* course, where it is repeatedly stated that students will gain appreciation of NOS positions and issues, and competence in NOS thinking, rather than declarative knowledge of NOS. It is important to stress these points: First FOS claims should not be presented as dogma, to do so is to confuse education with indoctrination; and second most, if not all, statements about FOS are subtle, and recognition of this subtlety simply depends upon having historical and philosophical (HPS) awareness. Both these points have implications for the very vexed and much-written up topic of the assessment of FOS and NOS learning (Rudge & Howe 2010).

It is unrealistic to expect students, or trainee teachers, to become competent historians, sociologists or philosophers of science. We should have limited aims in introducing FOS questions in the classroom. Teachers should aim for a more complex understanding of science, not a total, or even a very complex, understanding. Fortunately philosophy does not have to be artificially imported to the science classroom, is not far below the surface in any lesson or textbook. At a most basic level any text or scientific discussion will contain terms such as 'law', 'theory', 'model', 'explanation', 'cause', 'truth', 'knowledge', 'hypothesis', 'confirmation', 'observation', 'evidence', 'idealisation', 'time', 'space', 'fields', 'species'. Philosophy begins as soon as these common and ubiquitous terms are explained, amplified and discussed.

There is no need to overwhelm students with 'cutting-edge' philosophical questions. They have to crawl before they can walk, and walk before they can run. This is no more than commonsensical pedagogical practice. There are numerous low-level philosophical questions that are legitimate FOS questions: What is a scientific explanation? What is a controlled experiment? What is a crucial experiment and are there any? How do models function in science? How much confirmation does a hypothesis require before it is established? Are there ways of evaluating the worth of competing research programmes? Did Newton's religious belief affect his science? Was Darwin's 'damaged book' analogy a competent rely to critics who pointed to all the evidence that contradicted his evolutionary theory? Was Planck culpable for remaining in Nazi Germany and continuing his scientific research during the war? And so on.

Likewise history is unavoidable. Texts are replete with names such as Galileo, Newton, Boyle, Hooke, Darwin, Mendel, Faraday, Volta, Lavoisier, Dalton, Rutherford, Curie, Bohr, Heisenberg, Einstein, and others. History 'lite' begins when teachers, as Westaway was quoted earlier, 'talk to [students] about the personal equations, the lives, and the work of such' figures. And encourage students to do their own research on these scientists. History 'full strength' begins when the experiments and debates of these figures are reproduced in the classroom; when 'historical-investigative' teaching is practised (Kipnis 1996, 1998).

Other Features of Science are on daily display in newspapers, TVs and the internet, where accounts of socio-scientific and techno-value debates about genetics, agro-business, climate change, GM crops, global warming, and so on are constant features. If understanding FOS is embraced as a curricular goal, then well prepared teachers should be able to elaborate a little on these matters and facilitate useful classroom discussion and learning.

Twelve years ago I wrote:

> Science educators should be modest when urging substantive positions in the history and philosophy of science, or in epistemology. …Modesty does not entail vapid fence-sitting, but it does entail the recognition that there are usually two, if not more, sides to most serious intellectual questions. And this recognition needs to be intelligently and sensitively translated into classroom practice. (Matthews 1998, pp.169-170)

The change of focus from NOS to FOS greatly facilitates this orientation. NOS research has concentrated on the nature of scientific knowledge; FOS includes this, but is also concerned with the processes, institutions and cultural and social contexts in which this knowledge is produced.

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