Shedding Light on the Nature of Science through a Historical Study of Light

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Abstract

This paper takes the position that inclusion of elements of the nature of science (NOS) in the science curriculum can support the inquiry learning approach and fulfil the requirement for scientific literacy. It highlights the inadequacy of NOS conceptions even amongst teachers and the need for professional training in this area. It seeks not also to be a primer for science teachers on the current conceptions about the NOS but also to instil a sense of wonder and appreciation for the nature of light. It is suggested that historical case studies on the nature and theories of light be used as a platform to reinforce ideas about the NOS. This paper contends that the learning of the NOS (or learning about science) rather than done in isolation, is best carried out together in the context of learning and doing science. The challenge for educators is to draw connections between learning science, learning to do science, and learning about science together so that they reinforce one another to fulfil the intended outcomes of the science curriculum.

Introduction – NOS, Inquiry and Scientific Literacy

The information society, characterised by the ever shortened shelf life of knowledge, demands a school curriculum that will provide a good basis for lifelong learning and a preparation for life in a modern democracy. In his maiden National Day Rally speech, Prime Minister Lee Hsien Loong (2004) remarked that the school syllabus should be trimmed to allow:

> ...more space for them (students) to explore and discover their talents and also more space for the teachers to think, to reflect, to find ways to bring out the best in their students and to deliver quality results. We've got to teach less to our students so that they will learn more.

Science, in particular, has progressed tremendously over the last few decades that it would not be possible for schools to keep teaching more and more content. This means that teaching for depth of understanding of important science concepts should take precedence over the mere recall of science facts. In fact, this has been one of the basic premises held by Project 2061, a curriculum reform initiative to improve scientific literacy founded by the American Association for the Advancement of Science (AAAS). It views an overstuffed curriculum as impeding the acquisition of deep understanding as it places a premium on rote learning. The challenge then is to extract a set of key scientific concepts essential to science literacy and to teach it more effectively. This will invariably result in a shift from a content-dominated science curriculum to one which emphasises inquiry, leaving more time for discussion, reflection and analysis.

In the National Science Education Standards (National Research Council, 1996), the authors describe the Science as Inquiry content standard in this manner:

> Students at all grade levels and in every domain of science should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments.

As an addendum, Inquiry and the National Science Education Standards (National Research Council, 2000), was published to serve as a practical guide for the various educational stakeholders to respond to the Standards' call for an increased emphasis on inquiry. The most pertinent argument for adopting the inquiry approach is that it better reflects how scientists engage in scientific investigations and better facilitates conceptual change and understanding in our pupils.

An important goal of science education is to develop a scientifically literate citizenry, capable of making informed judgments about various scientific knowledge claims and their applications. The ability to recognize and refute poor scientific arguments and be active participants in debates involving scientific issues that impact on daily life becomes important in an increasingly democratic world shaped by science and technology. However, the overemphasis on 'what we know' at the expense of 'how we know' results in a science education which too often leaves students only able to justify their beliefs by reference to a textbook or a teacher as an authority. When confronted by a new scientific claim, it leaves them poorly equipped, without a functional understanding of the processes and practices necessary to evaluate the claim.

The Beyond 2000 report (Millar & Osborne, 1998) echoes the cultural and democratic justifications for an understanding of science. The authors believe that young people need an understanding of how scientific inquiry is conducted – to help them appreciate the reasoning which underpins scientific knowledge claims. The problem with current science curriculum is that it:

> ...can appear as a 'catalogue' of discrete ideas, lacking coherence or relevance. There is an over-emphasis on content which is often taught in isolation from the kinds of contexts which could provide essential relevance and meaning. Insufficient emphasis is given to showing the tremendous intellectual achievement such ideas represent, and how they have transformed our conception of ourselves and the world we inhabit. The existing stress on content limits the study of components such as the nature of science; the role of scientific evidence, probability and risk; and the ways in which scientists justify their knowledge claims – all of which are important aspects necessary to understand the practice of science.

It envisages a 21st century science curriculum that provide young people with the key ideas-about-science that will help them in understanding the major 'explanatory stories' or themes.

NOS Myths and the Need for Teacher Training

It has been documented that many students are leaving school with naive, deficient or distorted views or ideas about science. Common myths include:

? A general and universal scientific method exists; scientific inquiry is a simple algorithmic procedure
? Hypotheses become theories which become laws
? Experiments are the principle route to scientific knowledge
? Experiments are decisive and can prove if a scientific theory is correct
? Science is a value-free activity; scientists are particularly objective
? Science involves more of logic and analysis rather than creativity and imagination

These myths or misrepresentations of science in the school curriculum are discussed in greater detail by McComas (1996) and Hodson (1998). It is argued that such myths are perpetuated because of the scant or tacit treatment of the nature, practices and processes of science by teachers. Driver, Leach, Millar, & Scott (1996) argue that:

> Some explicit reflection on the nature of scientific knowledge, the role of observation and experiment, the nature of theory, and the relationship between evidence and theory, is an essential component of this aspect of understanding of science.' (p. 14)

Boo and Toh (1999) viewed that the majority of the science teachers studied need a concept change with respect to their views on the NOS; that is, they need to change from the traditional static view of science (the realist view) to the more current dynamic view of science (the constructivist view) as both a product and a process of constructing predictive conceptual models. Abd-El-Khalick & Lederman (2000) interviewed college students, many of them pre-service teachers, and discovered many of them held to the naive view that science is objective and certain rather than socially-constructed and tentative. Hence it was recommended that history of science courses explicitly address the NOS by teaching students to regard historical materials in context and by explaining the relevance of the historical science they are studying with modern science.

In his well cited review, Lederman (1992) traces the development of research into the views of teachers and students of the NOS and found that teachers' NOS views were often not well-developed. In a more recent study, Lederman (2002) showed that teachers' contemporary NOS views, while necessary for teaching, were not sufficient indicators of teachers' abilities to conduct science lessons infused with the NOS. To help students grasp a more accurate picture of the NOS involves both the explicit inclusion of elements of the NOS in the curriculum and the professional training of teachers. It must be stressed that the curriculum components of the NOS should not be taught in isolation or as 'stand-alone' facts. Hence the training of teachers entails not only the acquisition of the contemporary views of the NOS but also relevant pedagogical training that will enable teachers to operationalise and infuse some elements of the NOS into teaching strategies, activities, and material to support their teaching.

Using the History of Science to Teach the Nature of Science

History provides another avenue to the understanding of how science works and a chapter on historical perspectives is included in both *Science for All Americans* (AAAS, 1989) and *Benchmarks for Scientific Literacy* (AAAS, 1993). Although that chapter emphasizes the great advances in science, it is equally important that students should come to realize that much of the growth of science and technology has resulted from the gradual accumulation of knowledge over many centuries. Besides practical work in the laboratory, the authors of the Beyond 2000 report believe that case studies of some historical and contemporary issues involving science can improve students' appreciation and understanding of the complex relationships between evidence and explanation.

Osborne (2000) conducted a study using the Delphi technique to establish empirically whether there is significant support within the expert community for a 'vulgarised' account of the NOS that might be offered to school students. The results from the analysis of the study saw nine themes emerging for which there was consensus as important for inclusion in the science curriculum. Together with the results from analysis of eight curriculum standards documents (McComas & Olson, 1998), there seems to exist some consensus within the community concerned with science education about the elements of the NOS that should be taught. In particular, the high consensus rating on the theme 'historical development of scientific knowledge' supports the notion that the history of science should have a place in the science curriculum.

It is cautioned, however, that the history of science, as anything else, can be misused and lead to a mistaken view of science. Martins & Silva (2001) cited Towne's (1993) attempt to use Newton's original 1672 paper on the theory of light and colour as an oversimplified and inadequate use of the history of science. For example, to suggest the notion that 'experiments talk by themselves' and that the results from Newton's experiments lead to an easy and natural inference to a particular theory is a myth. In fact, when Newton undertook his studies on colours, he had several theories about light and carried out his experiments to determine which was correct. Hence when studying a piece of primary scientific source, care must be taken not to simply treat it as a detached piece of work without knowledge of its context, experimental basis and the rival theories of the time.

Light and Optics in the School Curriculum

Light and optics is a wonderful subject for school study. You can teach some facet of it at every grade level and it has extensive applications and everyday phenomena associated with it. The study of light begins at the primary level with recognizing the sun as the primary source of energy, how shadows are formed and how we actually see. The three laws of geometrical optics – law of rectilinear propagation, law of reflection and law of refraction, are typically introduced at the secondary level. Additionally, students will learn that light is a transverse wave travelling at high speed and is part of the electromagnetic spectrum. The principle of superposition which gives rise to phenomena such as interference and diffraction is next introduced at the junior college level. The idea of light consisting of photons but with different frequencies, giving rise to the emission and absorption spectra is further explored. Lastly, electron diffraction and the photoelectric effect are used to explain the concept of wave-particle duality.

The table below summarises some of the key concepts and learning objectives for light and optics at the various levels of the school curriculum:

Primary	Secondary	Junior College
? Light (from sun) as energy ? Shadows ? Reflected light off objects allow us to see them	? Light travels at a high speed ? Reflection, refraction & dispersion of light ? Light as part of the EM spectrum ? Light as a transverse wave ? The wave-speed equation $v = f\lambda$? Laws of reflection & Snell's law ? Refractive index ? Convex lens	? Polarisation as a property of transverse waves ? Principle of superposition ? Diffraction and 2-source interference ? Photoelectric effect as evidence for the particulate nature of light ? Electron diffraction as evidence for the wave nature of particles ? de Broglie wavelength $\lambda = h/p$? Emission and absorption spectra

Its 2,500 years of history is extremely rich and can be taken to be representative of how science works and evolved. Besides being taught the set of specific curriculum learning objectives at the various grade levels, it will be useful at some later point of their school life (upper secondary onwards) to engage in historical case studies on light and optics. This not only allows some opportunity for the integration of the related concepts but serves as a platform to help students appreciate how science is being done. It is also particularly suited to as a topic for inquiry as students already have ideas about light but yet surprises on the study of light still await them.

In his study involving children's ideas on light and vision, Selley (1996) found that the 10- to 11-year-old children studied predominantly held to the Cooperative Emission model of vision. This model requires light from the eyes (the visual ray) to meet up, at the object to be seen, with 'real' light from the source. He argued that the process of mapping experience to a model was more important than the content of that model. In fact, he warned that teaching only the 'correct' theory or model to explain scientific phenomena or experiments might lead to undesirable consequences. Pupils may simply rote-learn intuitively implausible statements leading to an undermining of their faith in the usefulness and reality of school science. Such might well become a real possibility, especially in assessment-driven education systems. To promote effective learning, specific contents of the students' alternative conceptions must be surfaced and student activities conducted to challenge their prior knowledge that will stimulate real conceptual change. Interestingly, the conceptual change which students undergo appears to be similar to the historical development of optics as also noted by Galili (1996).

A Survey of the History of Light and its Related Theories

The question about the nature of light has baffled scientists ever since the time of the ancient Greeks. Early notions of light were religious in nature and early explanations by Greek philosophers on the nature of light were intimately related to the explanation for the mechanism of sight. Broadly two competing schools of thought existed – the wave theory and the particle theory. One school held that light was some kind of impulse or wave transmitted through a transparent medium. Another proposed that light consisted of corpuscles or particles coming from luminous objects.

The story of light can be summarized simply as follows: Isaac Newton (1642 – 1727) held to the corpuscular theory of light mainly because of the observation that light travelled in straight lines and this remained the generally accepted view till the late 1700s. Then came Thomas Young (1773 – 1829) with his double-slit interference experiment which favoured the wave theory of light, first proposed by Christian Huygens (1629 – 1695).

In the mid 1800s, James Clerk Maxwell proved that electricity and magnetism were integrally inter-related phenomena and his equations revealed light was a kind of wave, consisting of a special interlocked pattern of oscillating electric and magnetic fields. Such an electromagnetic wave was actually found to exist and Maxwell's calculations could even yield a result for its speed, which was found to be exactly the same as the speed of light. These experiments, for some time, demolished the views in the minds of some scientists about the corpuscular theory and the wave-theory of light, based on solid evidence came to be universally accepted.

Finally, in the early 1900s, the photoelectric effect was given an explanation by Albert Einstein, for which he was later awarded a Nobel Prize. He used the principle of quantisation that was introduced by Max Planck. He suggested that light, contrary to the then popular wave-theory, consist of quanta of particles, which he named photons. The latest major contribution to an understanding of the nature of light has been the quantum mechanical picture of light contained in quantum electrodynamics developed by Richard Feynmann and others. A popular exposition of this theory can be found in Feynmann (1990). The dual nature of light is still a highly active research area (e.g., in single-photon experiments) and other recent discussions on the elusive nature of light can be found in OPN Trends (2003).

A summary of the various theories of light is given in the table below:

The emission theory	The emission theory states that the ‘fire’ from the eye sends out invisible probes in order to see objects.
The reception theory	The reception theory states that light emitted from luminous sources or reflected by ‘secondary sources’ causes us to see objects.
The corpuscular theory	The corpuscular theory states that light consists of corpuscles or particles that travelled in straight lines.
The wave theory	The wave theory states that light is essentially a wave and obeys the principle of superposition of waves.
The electromagnetic theory	The electromagnetic theory states that light is an electromagnetic wave. It is a transverse and travel at the speed of 3 ? 10^8 ms^{-1} in vacuum.
The quantum (wave-particle) theory	The quantum theory states that light has both wave and particle natures. Light is considered to propagate as a wave function (with all possible propagation paths) that ‘collapses’ when it is observed or detected, with the interaction seen as if light consists of individual particles of light.

For more delightful and comprehensive accounts of the history and nature of light, the reader is encouraged to refer to the following texts: Ronchi (1970), Park (1997) and Clegg (2001).

NOS Revealed through Historical Case Studies on Light and Optics

Galili & Hazan (2001) developed and tested a new history-based course in optics for 10th grade students. It incorporated ideas, views and conceptions which constituted the early understanding of light and vision. They used the schemes from students’ alternative knowledge (Galili & Hazan, 2000) to guide the design of the new course. Results were encouraging and provided evidence of the beneficial use of the history and philosophy of science-based materials in regular school instruction. Students became aware of a variety of social, cultural and historical issues, while at the same time improved their disciplinary knowledge of the subject.

A study of the various proposed theories of light through the centuries can help students to recognize that scientific knowledge is based on evidence, models and explanations, and evolves as new evidence appears and new conceptualizations develop. Students can also better appreciate the criteria for judging between competing theories (Kuhn, 1977):

? Accuracy – consequences deduced from a theory should agree with existing experiments and observations.
? Simplicity – a theory should bring order to phenomena that, in its absence, would be individually isolated and confused.
? Explanatory Power - a theory should be internally consistent with other currently accepted theories. The consequences of a theory should extend far beyond the particular observations and laws it was initially designed for. Furthermore, a theory should have predictive power.

The following table outlines some elements of the NOS or ideas about science that can be gleaned through a historical survey of light, focussing especially on the dominant theories held at different periods. It illustrates how the development of scientific knowledge is often affected by the social and cultural milieu. It shows how scientists use various methods to study the natural world and how they propose explanations based on the evidence derived from their work. However, scientists do not always agree and oftentimes more than one idea can explain what they see. Theories come and go in science and the ones that will stand the test of time will be those that are able to explain both established and new phenomena.

Historical Case Studies & Explanatory Stories	Elements of Nature of Science & Ideas about Science Gleaned
<u>Emission versus Reception Theory</u> - Pythagoras (~500 BC): held to the reception theory of sight. - Empedocles and Plato (~400 BC): held to the emission theory of sight. - The Early Atomists: Leucippus and Democritus (~400 BC), and later Lucretius (~50 BC) held to the reception theory of sight. - Alhazen (~1000 AD): an Arab scientist who gave a number of arguments based on experiments to support the reception theory.	? The Greeks relied more on philosophical debate and pure thought rather than on experimentation to prove ideas. ? Even amongst the Greeks, there were opposing views on the mechanism of sight, highlighting the fact of the co-existence of rival scientific theories. ? Scientific Method and Critical Testing (science relies on empirical evidence).
<u>Particle versus Wave Theory of Light</u> - Newton held to the corpuscular nature of light and he (via prisms) understood white light to be composed of all the colours of the rainbow. He was able to use his theory to explain the 3 laws of optics: law of rectilinear propagation, law of reflection and law of refraction. - Grimaldi (1665) - observed diffraction (light propagation not necessarily truly rectilinear). - Huygens (1690) – wave theory of light. He saw a close resemblance between light and sound and reasoned that since sound consists of waves through air (or other media), light must be similar. Huygen's principle explained most of the observed phenomena of light such as reflection, refraction, and diffraction. - However, the prevailing view was that waves were a periodic disturbance of something, such as air and therefore required a medium for travel. So it was proposed that light travelled in the all-pervading 'tether'. - Questions on Newton's Theory: If light were a particle, ? how could light beams pass through each other without scattering? ? why should these particles have a constant velocity irrespective of the nature and temperature of the light source. ? why should some of the corpuscles be reflected and some be refracted when a light beam struck a transparent surface like water? What mechanism was there to determine which particular corpuscle was to be reflected or refracted?	? Scientists do not always agree and oftentimes more than one idea can explain what they see. ? Analysis and interpretation of data - Data do not 'tell' you anything; you have to come up with the idea to account for your theory. ? The role of modelling in science and the limitation of models. ? Observations are theory laden and subjective. ? Observation versus inference. ? Scientific theories cannot be proven. ? Scientific theories and laws differ in their functions and remain distinct from one another (this can be highlighted by making reference to the 3 laws of optics as opposed to the theories about the nature of light). ? The idea of a model/theory as a description of reality or observed phenomena. ? Evidence, models and explanation ? A good theory should strive to explain the related phenomena. ? There exists more than one theory to explain a certain phenomenon. ? Theories come and go in science and the ones that will stand the test of time will be those that are able to explain both established and new phenomena. ? Scientific knowledge is based on evidence, models, theories and explanations, and evolves as new evidence appears and new conceptualizations develop.

Historical Case Studies & Explanatory Stories	**Elements of Nature of Science & Ideas about Science Gleaned**
- Despite experimental evidence for a wave nature to light, the weight of Newton's opinion on the matter damped wave enthusiasts for 100 years. - Thomas Young (1803) – principle of interference: Able to explain the phenomenon of Newton's rings in terms of either cancellation or addition of wave amplitudes of light reflected from the two interfaces. Although Young's work was a huge advance on anything that has previously been known about light, his wave theory was not widely accepted for another 40 years. In England, particularly, he was ridiculed for opposing the indomitable might of Newton's legacy. - Fresnel (1819) – did experiments on diffraction and submitted a mathematical description of his model to the French Academy of Sciences. An interesting aspect was that Poisson, who formed part of the evaluation committee, had derived from Fresnel's theory that a bright spot should be produced in the centre of the shadow of an opaque circular disc, and this, he believed, would prove the wave theory to be erroneous. It turned out that when the crucial experiment was conduct, as instructed by Arago, the central bright spot did indeed appear! - According to Newton, the reason light rays are refracted on entering water from air was that water, being denser than air, attracted the light corpuscles downward, hence the bending. This meant that light should travel faster in water than in air. The wave theory, however, predicted the opposite. It was not until 1850 that Foucault showed that light travelled more slowly in water than in air showing that Newton was wrong.	? Science and questioning: the work of a scientist is the continual and cyclical process of asking questions and seeking answers, which then lead to new questions. This process leads to the emergence of new scientific theories and techniques, which are then tested empirically. ? Bias & Prejudice in Science. ? Scientists do not always agree; sometimes more than one idea or theory can explain what they see. ? Sometimes there is insufficient evidence to authoritatively conclude which theory is correct (or at least not proven false). It takes new evidence to establish which theory is correct.
<u>The Electromagnetic Theory of Light</u> - James Clerk Maxwell (1873) – known for merging the phenomenon of electricity and magnetism in a single theoretical framework with his set of 4 famous equations. Interestingly, from his expressions, a wave equation for an EM field can be derived and he found that $c2=1/\mu o \varepsilon o$ where c remarkably coincided with the speed of light in vacuum. As a consequence, he suggested that light waves must be electromagnetic in nature.	? The importance of Theory (Maths foundation). ? Empirical versus theoretical scientific exploration. ? Synthesis of scientific knowledge. ? Not all ideas in science are simply 'discovered'. Science ideas and explanations are often invented and involve human inference, imagination and creativity. ? Underlying order in the world – simple models. ? Elegance – what makes up a good theory.
<u>The Quantum Theory of Light</u> - Heinrich Hertz (1887) discovered that electrons could be emitted from metal if a certain light was allowed to shine on it.	? Science and Certainty – provisional nature of science, scientific knowledge is tentative; it is not static and convergent but changing and open-ended.

Historical Case Studies & Explanatory Stories	Elements of Nature of Science & Ideas about Science Gleaned

- Max Planck (1990) suggested that light was transmitted and absorbed in small bundles or quanta of energy in order to explain the light spectrum emitted by hot objects (black body radiation).
- Einstein (1905) made the bold assumption that light consisted of tiny energy quanta in order to explain the photoelectric effect observed by Hertz.
 	
- The beginning of the 20th century saw the rise of the theory of relativity and the theory of quantum mechanics. Amazingly, both theories had their origin in puzzlement over the nature of light, and both eventually led to a very different understanding of light phenomena.
 	
- Orbiting Earth versus 'Orbiting' Electron
Causality – when electrons jump from a higher orbit to a lower one, there is no cause determining this quantum leap, it just occurs in a random manner according to a probabilistic law.
Continuity – again the jump is a quantum leap with no intermediary steps or continuity between the two states.
Determinism – the exact position of the electron not known but position around the nucleus described by a probability distribution.
	? 'School science' versus 'Professional science': one appears to have the right answers with teachers/textbooks as the authority; the other is more tentative and with unknown answers having no outside authority except within the own scientific community - peer reviewed results.
	? HOS is both evolutionary and revolutionary – the concept of paradigm shifts (Kuhn, 1970).
	? Science is socially and culturally embedded.
	? Creativity - science is an activity that involves not just logical reasoning but creativity and imagination as well.
	? Diversity of scientific thinking - that science is carried out not just by experiments but by observations or thought experiments. Science uses a range of methods and approaches and that there is no one scientific method or approach.
	? 3 Radical Shifts in Philosophical Principles in Science. Science no longer characterized by the principle of:
	  ? Causality – that every event occurred with specific causes existed prior to the event.
	  ? Continuity – that the trajectory of a particle in motion is made infinitely small steps, joined in a continuous manner.
	  ? Determinism – that natural phenomena occur according to precise laws, resulting in unambiguously determined outcomes.

It will be essential that as students learn the various concepts about light and glean lessons about the NOS, that they be given the opportunity for 'hands-on' laboratory activities and experiments. For example, the laser could be harnessed to re-enact Young's double slit experiment, determine the refractive index of a liquid or to find the speed of light. This will serve to better integrate student learning. However, it must be stressed that the laboratory activities must be accompanied by careful mediation on the part of the teacher to explicitly guide the process of these activities and to draw attention to specific elements of the NOS. Otherwise, many of these aspects of the NOS may be easily glossed over by students. A more holistic way is to involve the students, as novice researchers, in conducting well-designed scientific investigations to stimulate their appreciation and understanding for processes involved when engaged in scientific inquiry.

Conclusion

This paper has argued for the reduction of content syllabus so that explicit elements of the NOS in the science curriculum can be included to support the inquiry learning approach. This is not only beneficial for future students involved in scientific work but also for the scientific literacy of the general populace. To fulfil the intended curriculum objectives regarding the NOS, it is crucial that teachers be given the necessary training so that they are able to build a repertoire of their NOS pedagogical content knowledge. It has been argued that historical case studies in light and optics can be used as a platform to draw out lessons about the NOS and provide a more logical structure for the teaching of the concepts associated with light and optics. As a final note, it is stressed that the inquiry learning approach necessitates that students be given the opportunity to carry out scientific investigations, so that understanding of science concepts and learning about how science works take place in the context of doing science. The challenge for educators is to draw connections between learning science, learning to do science, and learning about science together so that they reinforce one another to provide the right kind of learning experiences for students that will fulfil the intended outcomes of the science curriculum.

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