Teaching the Nature of Science: What Illustrations and Examples Exist in Popular Books on the Subject?

WILLIAM F. McCOMAS

Rossier School of Education, University of Southern California, Los Angeles, CA 90089-4031
213-740-3470 mccomas@usc.edu

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Abstract: With increasingly widespread agreement that the nature of science (NOS) must be part of the K-12 science curriculum and emerging consensus on the specific elements that should be the focus of such instruction, this study moves on the next phase of work in this area by suggesting illustrations from the history of science to exemplify core NOS issues appropriate for use in NOS instruction. This study builds on a previous investigation (McComas, 2005) of eight recent NOS books written by HPS experts for general readers but now analyses these books not for NOS content, but for illustrations and examples to help make core NOS principles more concrete in the minds of learners. The rationale for the use of these books is that these experts, who have written books from different perspectives all focusing on the nature of science, are in the best position to recommend examples accessible to general readers, hence would also be appropriate for K-12 learners. The analysis has revealed that these authors have collectively provided approximately 80 unique historical vignettes in fields ranging from astronomy to physics. IT was noted that these experts used these historical illustrations for purposes that may or may not have been linked to the core NOS principles. The earlier study revealed 23 distinct areas targeted for inclusion in this range of books, but 9 are considered NOS core principles appropriate for K-12 instruction. Finally, the unique historical examples were linked with the core principles even if this was not the intended use of such examples in the original texts. The result of this process is an extensive set of illustrations (see Appendix A), from a variety of scientific disciplines, associated with important ideas-about-science and available to inform teachers, textbook writers and curriculum developers.

Keywords: nature of science, history of science, science pedagogy

Purpose

There is little doubt among science educators and others interested in science curriculum reform that a robust and authentic science program must contain elements of the nature of science if students are to understand and appreciate the scientific enterprise beyond the simple transmission of the facts of science. The nature of science (NOS)[1] is closely related to but is not that same as the history and philosophy of science (HPS). NOS might best be defined as a "... hybrid arena which blends aspects of various social studies of science including the history, sociology and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of which science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors." (McComas, Clough and Almazroa, 1998, p. 4). What results from a review of science by social scientists might best be seen as akin to trying to drink from a fire hose; the descriptions,

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[1] The author is aware of suggestions that we label "nature of science" as "nature of sciences" or "ideas-about-science." The rationales for these new labels are clear. There are historical and philosophical differences in the rules and traditions of the practice of science in biology when compared with chemistry when compared with physics, for instance, so we really should be discussing the nature of the sciences rather than implying a single overarching view of science as if it were identical across all disciplines. Some have argued that changing the term completely to ideas-about-science would be a solution to this problem. However, since the term "nature of science" is so well established in the literature, this paper will continue its use here with full appreciation of the criticisms of it that have appeared lately.

recommendations, concerns and analyses offered by these experts are vast, deep, interesting, occasionally incomprehensible and in their raw form, almost useless to the science teaching community.

The encouraging news is that the science education community has in recent years converged on a consensus view of the key NOS ideas appropriate for the inclusion in the K-12 science curriculum. Principally, Osborn, Collins, Ratcliffe, Millar and Duschl (2003), McComas (2005, 1998), Lederman (2002), and McComas, Clough and Almazroa (1998) have suggested surprisingly parallel sets of NOS content goals for K-12 science teaching that do not oversimplify science itself or overburden the existing science curriculum. A suggested list of such core ideas is provided in Table 1. The study reported here is designed to provide an additional data source as to the NOS core content elements as we continue to wrestle with this important issue. In recent years, standards documents such as the U.S. National Science Education Standards (NRC, 1998), many of the forty-nine U.S.state recommendations, and a wide number of non-U.S. education authorities (McComas and Olson, 1998) include aspects of the nature of science recommended as essential elements in science instruction. This focus on the nature of science is encouraging but even as educators embrace it as a vital aspect of science teaching, there will be the inevitable concerns about how to teach it. This paper is a partial response to this question as it seeks to provide examples that teachers may use to illustrate important aspects of the nature of science.

TABLE 1

A list of core NOS ideas appropriate to inform K-12 curriculum development, instruction and teacher education (McComas, 2005)

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1) Science demands and relies on empirical evidence.
2) Knowledge production in science shares many common factors and shared habits of mind, norms, logical thinking and methods (such as careful observation and data recording, truthfulness in reporting, etc.)
    - Experiments are not the only route to knowledge
    - Science uses both inductive reasoning and hypothetico-deductive testing
    - However, there is no one step-wise scientific method by which all science is done
    - Science has developed through “normal science” and “revolution” as described by Kuhn
3) Scientific knowledge is tentative, durable and self correcting. (This means that science cannot *prove* anything but scientific conclusions are still valuable and long lasting because of the way in which they are developed but mistakes will be discovered and corrected as part of the process)
4) Laws and theories are related but distinct kinds of scientific knowledge. Hypotheses are special, but general, kinds of scientific knowledge).
5) Science has a creative component.
6) Science has a subjective element. (Ideas and observations in science are “theory-laden”; this bias potentially plays both positive and negative roles in scientific investigation).
7) There are historical, cultural and social influences on the practice and direction of science.
8) Science and technology impact each other, but they are not the same.
9) Science and its methods cannot answer all questions. (In other words, there are limits on the kinds of questions that can be asked of science).

Rationale for the Study

This study is a response to the desire of how best to illustrate key NOS elements though historical examples that may be used to inform curriculum design, textbook presentations and classroom practice. The central rationale for the selection of the books and this research agenda is that much might be learned about the most appropriate NOS content by examining works written by experts in HPS for non-scientists ostensibly to enhance science literacy and encourage interest in this domain. This study builds on an earlier one (McComas, 2005) in which the content of these books was reviewed to reveal the elements of the history and philosophy of science that these authors believed to be important for the education of scientifically literate members of the general public. These same books have again been consulted to glean from them a range of examples that could be used to exemplify aspects of the nature of science. As a result of this study, a set of illustrations, examples and anecdotes linking NOS content to real-world examples is now available to enhance instruction. It is worth mentioning that a limitation of this approach is that there may be other useful and engaging historical illustrations that could exemplify important NOS issues are not revealed simply because these authors choose not to include them. However, the variety and focus of the books involved minimize this potential problem.

The objective of the study is to use these texts as information sources about what the relevant content standards might be in the area of the nature of science coupled with potentially applicable and useful examples of NOS from the real world. This use of historical examples to support science learning is not new. In fact, the AAAS Science President's Scientific Research Board Policies Commission in 1947 stated that "Much more use should be made of the history of science with its adventure and dramatic action, which appeal strongly to young people's interests and rouse their imagination" (cited in DeBoer, 1991, p. 132). The U.S. National Science Education Standards (NRC, 1996) feature and recommend the history and nature of science prominently. At the high school level, the Standards specifically state that "as a result of the activities in grades 9-12, all students should develop understanding of science as a human endeavor, nature of scientific knowledge, historical perspectives" (p. 200).

Using History in Science Instruction: A Brief Overview

Although the use of historical examples and cases in science teaching is not new, it has only infrequently been successful. Scientist and President of Harvard James Conant in advocated the view that students could learn much about how science functions but having students read and discuss historical cases. Conant (1948) developed a series of case studies based on historic scientific discovers – usually from the seventeenth through nineteenth centuries -- and believed that by engaging these authentic examples, students could discover important lessons about the practice of science.

Klopfer and Cooley (1961, 1963) expanded on the strategy developed by Conant and wrote a series of history of science case (HOSC) studies for secondary students (1964-66). The proposed series of booklets featured selected readings extracted from primary sources on topics such as the discovery of the halogen elements, cells, bio-electricity and the speed of light. Students were to read the historic account and in many cases reenact aspects of the discovery. Regrettably, not all of the proposed booklets were published even though Klopfer and Cooley showed that "students who study under the HOSC instruction method attain a significantly greater understanding of science and scientists . . . than those who do not" (p. 39).

It is fair to say that the case study approach made almost no impact on the teaching of science and even in programs that featured historical elements, such as Harvard Project Physics (Rutherford et al., 1964) students were expected to make their own conclusions about the nature of science and the work of scientists. This approach remains the norm. In most texts, the inclusion of historical examples seems more of an afterthought than an instructional imperative. Students may read a short inclusion about the life of Darwin, Newton or Einstein, but rarely do these discussions extend beyond the barest of details and hardly ever are they used to make substantive points about the NOS.

Proposals have been made to consider the use of cases and historical illustration, (Lochhead & Dufresne, 1989) in science instruction or in teacher education (Devons & Hartmann, 1970; Teichmann, 1986) but there has been surprisingly little impact of these proposals. The question is whether educators fail to see the value in these methods, lack the methods to apply these methods in the classroom or simply do not know that such methods exist.

Method

This study focused on two basic questions:

1) What kinds of examples are provided and from what scientific domains are examples drawn by these authors to illustrate important aspects of the nature of science?
2) What historical examples included in these books might be useful in illustrating core NOS principles shown in Table 1?

To address the first question, all historical examples from eight recent books on the nature of science for general readers were noted and analyzed. Next, these examples were removed from their original use and, if possible, applied to illustrate the list of nine core NOS principles recommended as goals for K-12 science instruction. As reported in the related study (McComas, 2005), there are many philosophical notions communicated in these books that are not considered core NOS issues. Such issues include, but are not limited to, logical probability, realism and anti-realism, logical positivism, incommensurability, covering laws, causality and many others. In some cases these non-core notions were accompanied by examples from the history of science. Occasionally the examples used could be used to serve as illustrations on the core notions even if that was not the authors' original intention.

Recent books written for general readers on the topic of the nature of science were located by searching key terms in lists of books-in-print and through a solicitation of suggestions of such works from members of the science education community interested in and knowledgeable about the nature of science. Books approximately spanning the past decade were deemed most appropriate for inclusion in the study since they are most likely to feature the most up-to-date and accurate descriptions of science. As we well know, interpretations of how science functions changes and one of the challenges with respect to any content in science is to ensure that it is current. With respect to this notion and the nature of science, we have only to be reminded by Duschl (1985). Slightly more difficult was the determination of a distinction between books designed for the general reader and those written primarily for use as texts in philosophy or history of science courses. This decision was made based on the level of language, book length, and the stated purpose of the book as described on web sites and/or on the book itself. These elements were considered jointly and a final set of books (noted with a star in the references section) was selected for analysis.

Following the book selection, a qualitative analysis of each text ensued using three investigators two of whom looked at all of the books and one of whom focused on a specific work. This analysis was conducted by carefully reading each book and noting the historical examples used to exemplify points about the nature of science. The basic rule followed in this pursuit was that a person or event had to be linked specifically to an aspect of the nature of science rather than generally used only to tell the story of the history of science. Several of the books used this second approach in which a time line of the progress and personalities was provided without specific references to what these historical anecdotes revealed about how science functions in any detailed fashion. An example of a "linked" element is provided below that has been included as a data point in this study:

Chalmers (1999) tells the story of told about how Galileo quantified his observations by recording data. He observed and recorded the positions of the moons or "starlets" of Jupiter to demonstrate that they were really orbiting the planet and were carried along with it in its own orbit around the Sun. This was a very important observation that would be hard to interpret in any way except to show that, in fact, these moons were orbiting another heavenly body just as Galileo hoped to convince doubters that the earth too was orbiting the sun. The author tells this story to make the point that observation (as empirical evidence) is vital in science – an important nature of science lesson. Had the story been told only to show the historical development of science without the accompanying link to an idea-about-science such as the role of observation, it would not have been noted for purposes of this study.

Data collection proceeded until scores of historical examples were gathered from the eight books, each related to a lesson about the nature of science. Each illustration was recorded only once even if several authors used the same example either for the same or a different purpose. At this point, the range of illustrations and examples and range of NOS lessons was examined to reach conclusions about the nature, extent and focus of the examples. This determination was made in a subjective fashion by examining the list holistically while looking for any patterns in the examples used, the science disciplines represented and the variety of the illustrations provided. Next, the master list of core NOS principles was used to organize and report specific historical examples that could be used to illustrate a particular core idea-about-science. Through this process, the examples were removed from their initial context in the book and considered entirely for their ability to exemplify one or more of the cores NOS principles. This final step is necessary to provide a set of practical conclusions that would not be possible if the examples were provided only in their original context. Many of these illustrations could be used to make a range of points about how science functions, but in many of the books examined, the authors have discussed issues beyond the core list of principles. In fact, the earlier study (McComas, 2005) reveals that these authors as a group discussed at least twenty-three unique NOS domains, but most would agree that the list presented in Table 1 is an appropriate, focused and achievable set of NOS goals to guide K-12 educational endeavors.

Data

From each book, the historical examples linked to nature of science issues were extracted the first time it was used. What this means is that any one example appears only once in the set of illustrations. These unique illustrations were analysed in two ways; first to see what scientific disciplines were represented by the examples (Table 2), and second to see which of the nine core NOS ideas might be best served by the use of that illustration (Appendix A).

TABLE 2
A list of scientific disciplines represented by the unique historical examples extracted from a set of eight current books about the nature of science.

Note, several of the examples were used by more than one author. For instance, several authors discussed the geoscience example of Alfred Wegener's proposal of continental drift, but it is listed only once in this chart below.

Discipline	Number of Examples	Percent
Physics	28	37%
Astronomy	17	22
Biology (Medicine)	11	15
Chemistry	8	11
Anthropology (Culture)	7	9
Technology (Engineering)	4	5
Geoscience	1	1

Results and Implications

The review of these books for the purposes of analyzing and considering the utility of historical examples of the nature of science has proved to be quite fruitful. The findings and related implications are provided here in categories ranging from those related to the scientific disciplines most frequently used as a source of examples to the issue of how explicit we must be in representing the nature of science to learners.

Using Examples in NOS Instruction

The majority of the K-12 learners are generally concrete learners rather than fully abstract thinkers. Therefore, the rationale for the providing examples of phenomena and ideas is clear. However, there were many examples of philosophical principles included in these books that were not accompanied by historical illustrations. To cite several such cases, Cromer (1993) discusses Bacon's role in stressing the value of observation measurements, experimentation, hypothesizing and deduction. Thompson (2001) stated that Francis Bacon initiated what was to become the norm of science by insisting that all knowledge should be based on evidence and experimentation. Sarder (2002) included much material of a philosophical nature, such as Popper's theory of falisifiability, but did not provide historical examples and illustrations. Wolpert (1994) quotes Max Planck who asserted that the pioneer scientist needs a vivid imagination and believed that ideas are not generated by deduction but by an artistically creative imagination.

While the link between the use of examples and students' enhanced understanding has not been well investigation, it is likely that the two are highly related. All involved in communicating NOS concepts, and other highly abstract notion, would be well advised to use illustrations to help make the lessons as concrete – and interesting -- as possible

The Source and Nature of Examples

As might be expected, the majority of the examples (37%) came from the physical sciences (Table 2). If one includes the astronomical examples the total percentage of examples from this branch of the sciences increases to 59% of the total. There are likely several reasons for this including the background of the authors themselves and the realization that many of the iconic scientists cited, such as Galileo, Newton and Einstein, were physicists. From a pedagogical perspective there seems to be at least one danger in continuing this trend. It is vital that students see that the core NOS ideas transcend the boundaries of the scientific disciplines. Perhaps, by extending the range of examples to involve all of the sciences students would be more likely to see the unity of science, appreciate the shared philosophical connections and avoid thinking of the governing principles as related only to some, but not all, of the disciplines. However, even as we endeavor to demonstrate the relatedness of the sciences, we must not ignore the fact that there are NOS distinctions between one discipline and another (McComas, 2003) and we should ensure that students gain the most accurate view possible. It is encouraging that by consulting the list in Appendix A, educators can now evoke illustrations from all science disciplines to support instruction about each of the core NOS principles. Dunbar, an anthropologist, has provided a wealth of examples from his field that extend far beyond those previously available and typically used.

Another interesting finding is that the vast majority of the examples come from historical rather than contemporary accounts. Einstein, Newton, Galileo and Darwin are frequently cited to demonstrate a lesson in the nature of science. Of course, these are fruitful and telling examples but students should also be given opportunities to see that the rules of the game of science operate today just as they always have. It is quite likely that these current accounts are harder to come by since the book of scientific discovery is still being written, but authors and educators should attempt to show that the work of these iconic scientists is mirrored in the day-to-day experiences of all scientists. Related to this recommendation is a fear that by hearing only about the work of the true scientific geniuses students may fail to recognize that all scientists are governed by and work within the same philosophical tradition.

The Purpose of the Example

Since these books each included elements of the nature of science beyond the list of core principles and no book offered a strong focus on all of the recommended principles it is not surprising that some examples were used that could not be linked to one of the core principles while other examples were used for purposes other than to illustrate a core principle even if these issue were discussed elsewhere. An example of this was found with the classic example of August Kekule, a chemist, who puzzled over the structure of benzene and, in a flash of insight saw a snake biting its tail and realized that the molecule was circular.

Okasha (2002) tells this story to make the point that the next step was to test the new model against the available data. Denny offers a more extended version and uses the example to talk about how well the new model explained things with respect to the evidence. These are wonderful uses of this example because we must communicate the necessary link between ideas, models and evidence and the story of Kekule make this point effectively. However, since neither of these authors focuses much on the role of creativity in science, they did not choose this example to demonstrate the necessary, but not sufficient, link between discovery and creative thinking. Wolpert (1994) included an entire chapter on creativity in this book, but he uses the story of Kekule as a warning that, to quote Pasteur, “chance favors the prepared mind.” Here the chance dream of a snake biting its talk could only have come about because of Kekule’s thinking about the issue. As Wolpert (1994, 63) states, ". . . such insights are far from typical and are invariably dependent on an enormous amount of earlier work and preparation."

The Level of Explicitness

There were many examples of philosophical principles included in these books that were not accompanied by historical examples. To several examples, Cromer (1993) discusses Bacon's role in stressing the value of observation measurements, experimentation, hypothesizing and deduction and Thompson (2001) stated that Francis Bacon initiated what was to become the norm of science by insisting that all knowledge should be based on evidence and experimentation. Sarder (2002) included much material of a philosophical nature, such as Popper's theory of falisifiability, but did not provide historical examples and illustrations. Wolpert (1994) quotes Max Planck who asserted that the pioneer scientist needs a vivid imagination and believed that ideas are not generated by deduction but by an artistically creative imagination.

Another interesting finding was that these authors often cited the same example while using it for different purposes. Consider the example of the French scientists Blondlot who believed that he had discovered a new kind of electromagnetic emission which he called the N-ray. He "saw" evidence of these rays even when the detector had been dismantled in a test by physicist R. W. Wood. Cromer (1993) applies this as an example of bias and subjectivity in science while Wolpert (1994) uses this same story to talk about the distinction between science and non-science.

As we have found with NOS instruction generally, it is important that these complex ideas be accompanied by an explicit discussion of the underlying principle rather than simply assuming that the message has been adequately communicated. For instance, Dunbar (1995) makes a strong cases for the distinction between laws and theories through as he discusses the kind of science practices by indigenous cultures. He shows repeatedly that members of these groups fully understand the patterns in nature (laws) and know when to hunt, fish, migrate, etc. However, he also makes the point that these individuals do not have an understanding of the reasons why the patterns in nature exist (theories). What he fails to do is to firmly show, by using the labels, that he is actually talking about the distinction between laws and theories. If students do not have an explicit opportunity to link lesson with NOS principle they will likely hear these accounts of science and consider them interesting but not particularly illustrative stories.

In conclusion, this project should not be seen as the final word or represent all examples and illustrations that may be used to help make concrete the core nature of science notions we wish to communicate to students. However, it has been interesting and enlightening to example a rich data source of such examples and to explore further the ways that the history of science can enliven the study of science.

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Appendix A

Historical Illustrations, Examples and Anecdotes Extracted from Popular Books on the Nature of Science Associated with Key Nature of Science Principles

#1 Science Depends on Empirical Evidence

- Galileo quantified and qualified his observations through recorded data. He observed and recorded the positions of the moons of Jupiter. He could then predict the future positions. When questioned by the scientific community he could confirm his observations. (Chalmers, 22-23).
- Galileo argued in favor of the Copernican view of the universe but his work was challenged by more conservative (traditional) thinkers not because his observations and calculations were found wrong but because his argument was based on observation and calculations, not theoretical understanding (Thompson, 41).
- Based on studies and observations Humboldt developed a theory of biogeography of how the physical conditions of an area influence the features of the ecosystem found there (Derry, 20).
- Descartes showed that the rainbow is not a heavenly signal of peace, but can be explained in terms of what happens to rays of light when they encounter raindrops (Sarder, 34).
- Train of events leading to the discovery of Neptune with Leverrier and Ades suggesting and undiscovered planet near Uranus (Chalmers and Derry, p. 48).
- Once the heliocentric model was accepted, observations were consistent with what the model suggested (Cromer).
- Variations in Venus' brightness called into question the earth centered model (Cromer).
- Copernicus used the work (evidence) of Ptolemy in his models but interpreted the evidence quite differently (Cromer).
- Brahe was the first modern astronomer to keeps detailed night-by-night records of his observations (Cromer).
- The neutrino was originally suggested by Pauli to explain nuclear decay but other scientists did not like its ad hoc nature (Dunbar, p. 99-100).
- 19th century chemists' results on molecular weight was no longer significant after the discovery of isotopes (Chalmers).
- Aristotle got right 32 of 24 findings that he studied directly (94%) and got wrong 10 of 12 findings that he did not study directly (83%) (Dunbar, p. 39).
- Newton and the universal law of gravitation is based in many observations (Okasha).
- Einstein's theory of the effects of gravity on light was observed in Africa and South America in 1919 (Thomson).
- Rayleigh (1890) cleared air of all gasses expect nitrogen in two different ways and found a discrepancy in the desnsity measurements of the product, this discrepancy lead to the discovery of argon (Derry, p. 42-3).
- Torricelli discovered air pressure by noting that it was possible only to move a water column up to 34 feet in height by suction. (Derry, p. 44)

#2 Science Share many Common Features

- Roentgen's discovery of x-rays was the results of both methodical work and serendipity (Derry, p. 11)**.**
- Jenner discovered the smallpox vaccine after careful observations and many tests of his hypothesis and modifications of his ideas (Derry, p. 24)**.**
- Galileo performed experiments in front of peers to validate his results (perhaps dropping balls from the Tower of Pisa); Galileo invalidated Aristotle's laws of motion in the public areas (Chalmers, p. 2)**.**
- 18th century alchemist Abu Musa Jabir ibn Hayyam used trial and error experimentation to discover new chemical reactions making him an important figure in the history of chemistry (Dunbar, p. 41)**.**

- Newton's gravitations theory made predictions about the paths the planets should follow. His predictions came from his observations of the planets (Okasha, p. 15)**.**
- There is no way to examine all bodies in the universe, therefore Newton used induction in the development of his laws of motion (Okasha, 37).
- Archimedes wanted to find out if a crown was made from pure gold. His used an established relationship between mass, density and volume to make judgments (Thompson, p. 56).
- The shift in understanding from Newton to Einstein is an example of a scientific revolution (Chalmers).
- Inductive reasoning (example of Down syndrome and the link to a particular chromosome pattern) (Okasha).
- Optical evidence supported Fresnel's wave theory of light, but modern physics shows that there is no ether, therefore there is nothing for the waves to move through (this is a false but empirically successful theory) (Okasha, p. 65).

#3 Science is Tentative, Durable and Self Correcting

- Crick and Watson deciphered the molecular basis for Mendel's genetic theory (Cromer, p. 40).
- Galileo theorized that the earth revolved around the sun, he was never able to prove his theory (Sardar and Van Loon, p. 42).
- Brahe's refutation of Copernicus' theory (even Brahe's estimates of the distance to the stars was too small) (Chalmers).
- Examples of the issue of cold fusion (Thompson) in physics and J. B. Rhine's work with ESP (Cromer) show science to be self correcting.
- Copernicus suggested that the size of Venus and Mars was due to visual perception problems, but Galileo showed that the different was real with the telescope (Chalmers).
- Einstein explained Brownian motion with the kinetic molecular theory rather than the electrical attraction originally thought (Okasha, p. 3).
- Hertz thought that the cathode ray was a stream of charged particles, Thomson rejected that finding with improved technology (Chalmers).
- Kepler's view of the solar system was superceded by Newton's (Chalmers).
- Newton's physics were enhanced by Einstein (i.e. mass of falling objects in a discharge tube) (Chalmers).
- The Phlogiston theory of combustion failed due to the increasing numbers of ad hoc notions (such as phlogiston must have negative weight) (Chalmers).

#4 Laws and Theories are not the Same

- Durkehim concluded that there were social "laws" at work that could be known statistically. Human behavior that could be measured and predicted (Thompson, p. 23).
- The Big Bang Theory had the ability to make accurae predictions of future observations (Thompson).
- Kamerlingh Onnes discovered superconductivity through a series of experiments. There was early effort to understand superconductivity on a theoretical basis, but it was not fully understood until John Bardeen devised a theory that supported Onnes findings and was accepted by the scientific community (Derry, p. 37).
- Darwin's theory of evolution was influenced by the ideas of Thomas Maltus regarding population growth and food supply. Natural selection explains evolution (Cromer, p. 40).
- Newtonian mechanics is enhanced by being firmly embedded in a grand theoretical scheme that correctly describes everything from the motion of protons inside a nucleus to expansion of the universe itself (Cromer, p. 12).
- Mendelian gentics is a theory that relies heavily on probability to explain characteristics that are passed from one generation to the next (Okasha, p. 36).

- Cavendish inverse square law of attraction (Chalmers).
- Frensel's theory of light predicted Amago and Maxwell's speculation about the displacement of the ether that led to the prediction of radio waves (Chalmers).
- Cause and effect science with multiple examples from Dunbar (Japanese fish catching, p. 44, W. African Fulani and cattle ranching, p. 44-5, Buran honey guides, p. 45, Maasi using natural resources, p. 52).
- Ancient Egyptians were able to predict the Nile flood, but not explain it (Dunbar).
- Copernicus produced a better model of the solar system but made no attempt to explain the motions of the planets (Wolpert, p. 44).
- "Agriculture was in progress at 7000 BC . . . cattle were domesticated . . ., but there is no reason to believe that the farmers had any more understanding of the science involved in agriculture that most Third World farmers have today. They relied on their experiences and learned from their mistakes" (Wolpert, p. 26).

#5 Science has Creative Elements

- Newton saw an apply fall from a tree thus giving him a link between the force of one object on another (force of earth on the apple) (Cromer, p. 139).
- Belgian scientists Kekule discovered the hexagonal structure of benzene. He arrived at this structure after a dream in which he saw a snake trying to bite its own tail. Then Kekule had to test the model against the facts. Scientific hypotheses are arrived at in many different ways, what matters is how you test them (Okasha, p. 79).
- Da Vinci observed nature carefully and considered possible applications that those observed mechanisms could have. He was fascinated by flying and created many inventions related to flying machines (Thompson, p. 10)
- Fleming discovered antiseptic action when he added his mucous to a bacterial culture and watched the lysozyme kill bacteria. Later, when he saw zones of inhibition around mold growing in bacterial colonies he noted the similarity to the lysozyme effect (Wolpert, p. 81).
- Wolpert provides dozens of examples of the role of creativity in science; Darwin is featured heavily.
- Mark Ptashne's search for the repressor protein as suggested by Jacob and Monod proceeded and succeeded in the face of many failures (Wolpert, p. 73).
- Pasteur; was it lucky that he discovered right and left handed molecules in racemic acid or that the had decided to study racemic acid in the first place? (Wolpert).

#6 Science has a Subjective Component (Theory-ladenness)

- Ptolemy believed that the earth was at the center of the universe. While observing, he saw inconsistencies and forced explanation for them to the fit the geocentric model (Cromer).
- Blondlot believed in the existence of N-rays and saw them even when the detector had been dismantled by physicist R. W. Wood (Cromer, p.166-7 and Wolpert, p. 141).
- Aristotle had many personal theories and found them difficult to dispel even when they did not fit the evidence. Example; a book moves when you push it, when you move your hand away the book stops moving. However, when you shoot an arrow, why does it keep moving? Aristotle believe that it was the air because it was the only thing in contact with the arrow (Cromer, p. 128).
- Lamarck believed that you could categorize species in terms of their complexity, with every species tending to evolve into something more complex. Lamarck believed that way in which this happened was through offspring inheriting traits that the parents developed during their lifetime (Thompson, p. 25).
- Galileo showed that the "man in the moon" is just a random arrangement of the darker, flat spots through observation with his telescope (Sardar and Van Loon, p. 33) .
- Biological classification (cladists vs. pheneticists) is an example of the subjectivity of science (Okasha, p. 606).
- Wolpert (p. 90-1) writes that McClintock's ideas about transposons (jumping genes) were rejected in 1950

because her ideas were premature for the remainder of the scientific community. "Stability of the position of genes on a chromosome [at that time] was fundamental to genetic thinking." (p. 91). It the late 1960's scientists discovered transposons in bacteria.

- Alfred Wegener's suggestion of continental drift was rejected by the established scientific community (Wolpert, p. 91).

- Milliken's oil drop experiment is a classic example of his prior expectations of what he should find (Wolpert, p. 96-7).
- Discovery of the Epstein-Barr virus in patients with Burkett's lymphoma by Epstein. He simply "knew" that the causative agent had to be a virus even though many others doubted him (Wolpert, p. 98-9).

#7 There are Culture, Political and Social Influences on Science

- Different cultures have different perceptual experiences. African tribes when shown a picture of a stair would not see a stair because their experience with such things are limited and rarely see 3D objects depicted in 2D (Chalmers).
- Many held the geocentric model due to religions reasons (authority) (Cromer).
- The Catholic church banned books explaining Copernicus' suggestion that the sun was at the center of the solar system . . . (Okasha, p. 3).
- Aristotle was held as such an authority that it was difficult to challenge his views. Copernicus and Galileo had a difficult time changing the views. (Thompson, p. 5).
- The space race between the US and USSR (Dunbar).
- Much of Archimedes work was driven by the needs of defense (the engines of war) (Dunbar, p. 164).
- Some have argued that a scientific tradition in India failed to develop because of religion objections (Cromer).
- The needs of war have resulted in many scientific and/or technological advances such as Haber and poison gas, the nuclear bomb projects, etc. (Sardar and Van Loon).
- There may be a mismatch between science and the needs of society with respect to inclusiveness (Sardar and Van Loon)
- Corporations are interested in some science (i.e the human genome project) but not in all (i.e. high energy physics) (Sardar and Van Loon)

#8 Science and Technology are Not the Same

- The invention of the telescope allowed Galileo to change Copernicus' ideas about the size of Venus and mars (Chalmers, p. 16-17).
- Hertz conducted a series of experiments on cathode rays, he concluded that cathode rays are beams of charged particles. J.J. Thomson conducted a series of experiments and concluded that cathode rays are beams of charged particles. Due to advances in technology, Thomson improved on and ultimately rejected Hertzs' experimental results (Chalmers, 32).
- Early Chinese civilization was technologically advanced (they created paper, silk production, detailed astronomy, etc.) However, their work was utilitarian, not explanatory and they did not develop a scientific program (Dunbar, 36).
- New instruments promoted the careful examination of the world. The telescope improved by Galileo and used by him to a controversial effect. Microscopes showed people images of things previously far too small to be observed by Robert Hooke (Thompson. p. 21).
- Robert Hooks and Henry Power disagreed about the "observable facts" of a fly (wing structure). This was due to different illuminations in the microscope. Hooke designed a way to clean up the problem and have uniform lighting in the microscope (Chalmers, 20).
- The telescope is frequently shown as an example of the interplay between science and technology

(Chalmers).

- Cars, airplanes, radios and TVs were developed in a trial and error fashion with jet engines and silicon chips derived from physics principles (Dunbar, p. 86).
- Wolpert (p. 30) used examples of bridges build by experiments rather than the application of the underlying physical principles or "theory." Models were built of a bridge in North Wales (1850's) but the "theory which could have provided an analytic approach to designing the structure had been published a few years earlier, but was ignored."

- Hertz in 1888 demonstrated the propagation of electromagnetic waves . . . [but] Oliver Lodge . . . recognized their importance for telegraphy" (Wolpert, p. 33)

#9 Science Cannot Answer all Questions (Science has Limitations)

- Indian civilization strongly demonstrates that human thought can develop and thrive for thousands of years without ever stumbling on the notion of scientific objectivity. Science is not the inevitable outcome of serious philosophizing (Cromer, p. 107).
- Emile Durkheim arugued that religion has a different rationale from science. Religion does not explain actions, emotions or the physical world. Religion is a comment of the nature of social life (Dunbar, p. 34).
- In Newtonian science, the law of gravity was a fundamental principle, it explained other things, but could not itself be explained (Okasha, p. 53).
- For some Darwin's theory of evolution clashes with the Bible. Others have found way to reconcile evolution with their faith. The Book of Genesis should not be interpreted literally, it should be regard as allegorical and symbolic. Darwin only conflicts with the biblical story in the literal truth (Okasha, p. 126).
- Nature of consciousness may not be explained by science (Okasha, p. 126).