A Textbook Case of the Nature of Science: Laws and Theories in the Science of Biology

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Abstract: The two concepts "law" and "theory" are among the most important elements of the nature of science. They represent both the tools and products of science itself. Unfortunately, the variable meanings of these terms both in general discourse and in other school disciplines results in much confusion with respect to their proper use in a science context. The project included the design of a six-part model definition for "law" and "theory" based on an extensive review of the literature of the philosophy of science with special reference to biology. These model definitions were then compared with those provided a range of secondary school biology textbooks. The majority of all current major U.S. secondary school biology texts were reviewed and analyzed with respect to how the concepts of "law" and "theory" were defined and applied in an attempt to determine whether students and teachers using such texts would gain an accurate impression of these terms and the distinction between them. This study focuses on biology instruction since a life science course is completed as a graduation requirement by virtually all U.S. high school students and as such serves as a widely shared educational experience in across the nation. The term "law" is rarely defined in any text but various laws such as those found in genetics are frequently included as examples. The term "theory" is frequently defined but with a wide range of completeness of the definitions although only rarely are theories in biology included as examples.

Keywords: law, theory, nature of science, science teaching

INTRODUCTION

The U.S. National Standards for Science Education (NRC, 1996) include a range of instructional recommendations related to knowledge of the underlying structure of the discipline of science. Objectives such as these extend the domain of science instruction to include aspects of the nature of science (McComas, Clough and Almazroa, 1998). Such objectives are increasingly common in many new documents specifying standards for science education (McComas and Olson, 1998). This trend that science instruction should focus on a deep understanding of how the discipline functions is encouraging but problematic.

We should be encouraged by the promise of the standards. If the recommendations are heeded, students will gain insights into the nature and structure of science extending well beyond the typical encyclopedia of scientific facts that characterize most science learning experiences. A potential cause for concern is the realization that few science teachers are prepared to discuss issues in the nature of science and many science texts contain shallow or incorrect views of the philosophical aspects of the discipline of science.

An additional problem is that only rarely do teachers explicitly target the "nature of science" as an important goal for instruction in spite of strong recommendations from U.S. state, national and many international science standards documents (McComas and Olson, 1998). Occasionally, such documents themselves are part of the problem by their lack of specificity. As a case in point, the guidelines for the national curriculum in India (National Council of Educational Research and Training, 2003) state simply that "the most important purpose of science teaching in general education . . . should be to fulfill the following seven dimensions of scientific literacy including [having an] understanding of the nature of science (p. 17)." The goal is laudable, but teachers and textbooks authors need more guidance in determining exactly what elements ought to constitute the "nature of science" for science teaching and learning. The *National Science Education Standards* (NRC, 1996) in the United States are somewhat more explicit but also lack several elements of the nature of science recommended by other related documents such as *Teaching about Evolution and the Nature of Science* (National Academy Press, 1998) .

An example of an important but neglected aspect of the nature of science involves the concepts of "law" and "theory." Facts or shared empirical observations are the foundation upon which all scientific knowledge is constructed, but what scientists do with those facts is key to a complete understanding and appreciation of the scientific enterprise. Unfortunately, many falsely believe that facts are built into theories and theories into laws in a sort of maturation process. This may lead to the misconception that laws are more valuable – and are thus more believable – than are theories. The implication of this misconception is that, with time, all scientific ideas will either become laws, will be discarded or somehow linger as mere speculations. This false hierarchy between theories and laws gives rise to the oft-heard expression "it's only a theory" particularly when one would like to discredit a scientific notion such as evolution. The lack of attention to the distinction between these terms clearly compromises student learning by permitting the misconception to go unchecked or by fostering the misconception in the first place.

In brief, facts or shared data and observations are the raw materials of science that may be used in a variety of ways. Such facts may be formed into a law or "a descriptive generalization about how some aspect of the natural world behaves under stated circumstances" (National Academy of Sciences (NAS), 1998, p. 5). Another distinct kind of scientific knowledge is a theory which is "a well substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses" (p. 5).

Laws and theories are both products and tools of science, but each has a distinct heritage and role. One does not become the other when more evidence is amassed (Horner and Rubba, 1978, 1979; McComas, 1997). In actuality, theories and laws are equally mature, important, useful and unique kinds of scientific knowledge. Understanding the fundamental distinctions and relationships between laws and theories is essential in fully appreciating and evaluating the work of scientists while gaining fluency in the language of science. Science class provides the opportunity for students to understand the roles and discrete contributions of laws and theories while providing opportunities for them to question their beliefs about these and other related issues in the nature of science.

PURPOSE

The purpose of the study reported here was to investigate how U.S. high school biology textbooks address a single element of the nature of science -- the distinction made between the terms “law” and “theory.” In the United States, virtually all graduating secondary school students will have taken a course in biology. Instruction in biology, therefore, becomes one of the few science learning experiences common to all students in the nation and as such is a useful point of analysis regarding the state of science education generally. Members of the international community may be interested in this in-depth analysis of biology education as a dominant aspect of science instruction in the United States while reflecting on the state of affairs in texts and classrooms closer to home.

This study extends earlier investigations conducted by Lewis (1988), and Lerner and Benetta (1988) which examined the use of the term “theory” in life science and biology textbooks and the work of Gibbs and Lawson (1992) that explored several issues in the philosophy of biology. This study provides a more complete examination since it involves the related concepts of “law” and “theory” and focuses on a wide range of biology texts. Biology is deemed a particularly important content area for analysis of this type because it is the most commonly studied science subject at the secondary level and is frequently the last required science course for many students at least in the United States. Furthermore, biology as a science discipline has historically been neglected from a nature of science perspective when compared to the more mathematical and mechanical sciences of physics and chemistry.

Method

This study employed a qualitative text analysis of the majority of all current high school (secondary) school general biology (N=13) and advanced placements textbooks (N=2) in use in the United States. This analysis required the development of model definitions for “law” and “theory” formulated through a review of the philosophy of science literature with particular relevance for the nature of biology. The elements of the model definitions are presented in Tables 1 and 2. This step was accomplished before any texts were reviewed.

Next, every instance of the use of the term “law” or “theory” appearing either in the narrative or glossary in each textbook was noted by two researchers who worked independently first to locate all such instances of the use of the targeted terms and then to compare the instances with the model definitions. The two researchers compared and discussed their results to ensure reliability. The number of instances of the appearance of either term was small and the complexity of the definitions provided in or implied by the text was slight so it did not seem reasonable or necessary to calculate a reliability coefficient since the task of locating and analyzing instances was ultimately not a complex one.

An issue that was beyond the scope of the investigation relates to implications provided in the text that a particular kind of biological knowledge was either a law or a theory. Therefore, unless the label “law” or “theory” was explicitly applied to a concept, the analysis did not include reading every statement in every text to determine if a student might think that an idea was law-like or theory-like because of the way that idea was presented by the authors. This is not a trivial point and it might be quite interesting to ask students whether they think that a particular idea is a law or a theory based upon what they know about these terms and what language the authors use in presenting them.

The Distinction between Laws and Theories

One of the major tasks associated with this analysis is to have models definitions of “law” and “theory” available for comparison with those provided in the texts. This task was accomplished by reviewing a large number of nature of science references particularly those with a focus on the philosophy of biology. The definitions provided below and summarized in Table 1 and 2 have been validated by the researcher both by examining points of similarity in the definitions from one reference to another and by considering the nature of the author cited. For instance, Michael Ruse and Ernst Mayr are well known and respected for their views on the nature of science in biology. However, this is not to say that there one would expect universal agreement with the definitions provided, but the rigor and selectivity used in developing the models has likely resulted in definitions that will be widely acceptable.

Laws

A scientific law (Table 1) is a basic principle, generalization, regularity, or rule that holds true universally. Laws are developed (some would say discovered) from facts and explain and predict individual occurrences or instances (Carey, 1994; Carnap, 1966; Mayr, 1988). For example, the law of gravity predicts the force of attraction between two objects given the masses of the objects and the distances between them. The particular example of the universal law of gravity is particularly inappropriate for many laws in biology because it is mathematical in a way that many biological principles surely are not. There is a school of thought in the philosophy of science that laws, by definition, must contain mathematical relationships but this is not a strict requirement when reviewing the bulk of the literature on this issue.

As will all philosophical discussions there is debate about the nature of laws in biology, leading several scholars to question if biology even has laws (Brandon, 1997; Hull, 1974; Ruse, 1970). Several issues lead to this question. First, the issue of universality is a sticking point for some philosophers of science who question the legitimacy of calling something a law if it does not hold true in all instances and at all times. By this criterion, even such well accepted notions as Newton’s laws and the gas laws are problematic. For instance, Newton’s laws of motion are valid only at speeds less than the speed of light and the gas laws are valid only within a certain range of temperatures. This issue of universality has particular relevance for biology. Some argue that it is not reasonable to call something a law even if it has law-like character here on Earth, such as the “law of independent assortment,” because we lack knowledge of its applicability elsewhere in the universe (Ruse, 1973). Frankly, there is little reason to believe that genetic transfer systems on other worlds would have evolved in such as way that a law of independent assortment should be expected. So, if the issue of universality with respect to extraterrestrial biological systems remains an issue, all putative laws in biology are likely doomed.

Another vexing issue is the problem of restriction in some biological laws. Unlike in the physical sciences, where it is possible to consider many generalizations as broad laws, in biology there are almost always exceptions to the rule. Again, an example relates to the validity and utility of the law of independent assortment which is limited to genes on separate chromosomes. In another example, Ruse (1973) points out that Bergman's Body Rule (the idea that the mammals are likely to be more rotund one approaches the poles) is true for only about 70% of animals living in such environments. This still seems like a useful concept but there is no way to know, in advance, which unstudied newly discovered mammal will follow the rule. The question is whether we will insist that the probability must be 100% before we can consider something a law.

However, if we maintain that Earth should be our frame of reference and with an understanding that biological generalizations are somewhat less firm than those in other sciences, it seems clear that there are principals in the life sciences that have law-like character and as such should be labeled accordingly. There can be no argument that Boyle's Law in the physical sciences and Mendel's Laws in biology do not have the same predictive power or range of applicability but it is clear that both ideas represent similar kinds of knowledge in terms of their impact on science, and for that reason they are both laws.

The definition of "law" provided here is grounded epistemologically in a claim of realism defined such that there is an external world that can be known to some extent by inquiring and testing. This claim has particular relevance for the assertion that laws are discovered rather than invented. Of course, some will not be convinced of this claim because a non-logical (i.e. creative) element is involved both in discovery and invention, but it seems prudent to acknowledge the potential criticism even before it is made. A realist perspective posits that there are regularities in nature that exist exclusive of those looking for them and than they regularizes or laws can be found or discovered and then described.

The issue of "explanation" is another potentially troublesome aspect of the definition. The kind of explanation provided by laws is not very satisfying but is still worth including among the functions of such generalizations. For instance, we might evoke Allen's Appendage Rule (the notion that mammalian appendages are generally shorter for those animals living near the poles when compared with similar mammals living elsewhere) as the explanation for why the legs of polar bears are short and fat and those of Malaysian sun bears are comparatively long and lean. Of course, this tells us nothing about the underlying ratio of surface area to volume and the conservation of heat that occurs when the relationship favors volume over surface area. Nonetheless, Allen's rule does "explain" the phenomenon that we see with respect to appendage length. In most instances, the most complete and pleasing explanation is to evoke a theory.
TABLE 1

Table 1: A definition of the term “law” includes the following aspects. This set of elements was used in assessing the use of the term “law” in the textbooks included in this study.

Scientific laws:

A) are validated by hypothetico-deductive[1] testing;
B) are supported by and based on many facts, experiments, and observations;
C) relate cause and effect relationships broadly (some would say, universally);
D) explain why particular *instances* occur (ex. objects fall at a particular speed because of the law of gravity);
E) predict future instances or occurrences of the relationship;
F) are generally considered to be discovered rather than invented.

Theories

A scientific theory (Table 2) is a conceptual scheme (that some would say is invented) bringing concepts, principles, hypotheses -- often from different fields -- together to explain a phenomenon (Holton and Brush, 2000) while addressing “mechanisms and causes of things or events” (Lewis, 1988, p. 344). Robust theories are those that have withstood repeated testing, adequately explain the laws that are related within its framework, and predict future observations. Losee (1993) adds that laws themselves are incorporated into theories and provide the points of connection between previously unconnected laws. As an example, consider how the kinetic molecular theory of matter, which posits that tiny moving particles that spread apart when more energy is applied, explains why a balloon expands when heated.

Unlike laws, it seems that there is little argument about the existence of theories in biology Lewis (p. 13, 1990) reports finding “700 theories [in science] . . ., 600 from biology and the remainder from other disciplines.” While his vision of a theory may be more encompassing than that of others, Lewis includes the germ theory, classification theory, theory of food webs, cell respiration, fermentation, meiosis, etc. among the many theories in the life sciences.

Like laws, theories are also designed to “explain,” but do so in a very different fashion. Laws explain instances (in a very unsatisfying way as seen in the previous description), but theories explain much more broadly. Evolution and its epistemological nature is useful to evoke at this point. Neither Charles Darwin or Alfred Russel Wallace, the co-discoverers of the *mechanism* of evolution, would rightly claim to have discovered evolution itself. The idea that populations of organisms change through time had long been suspected. However, both Darwin and Wallace are given credit for explaining how evolution could take place. Lewis (1986) has analyzed Darwin’s model of evolution and finds that it contains two elements, the “theory of descent with modification” (the evidence that evolution has occurred) and the “theory of natural selection”

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[1] Hypothetico-deductivism is considered by some to be *the* central method of validating scientific knowledge if not actually discovering such knowledge in the first place. Through this method, claims in the form of predictive hypotheses, are evaluated by deductive analysis by seeing how well those predictions match reality. If the predictions are supported by empirical evidence then the underlying hypothesis gains support. For an interesting debate on the role of hypothetico-deductivism in science, see Allchin (2003) and Lawson (2003).

(the five-step model explaining the mechanism). Lewis (1986) has correctly shown that theories have an underlying synthetic structure and that they have an explanatory role as their central tenet. Some have suggested therefore that theories are invented. Theories are arguments build up from facts, laws and inferences to explain phenomena rather than simply to describe phenomena so it seems reasonable to acknowledge that they are products of human inquiry related more to an act of creation than of discovery.

Table 2: A definition of the term "theory" would include the following aspects. This set of elements was used in assessing the use of the term "theory" in the textbooks included in this study.

Scientific theories:

A) are validated by hypothetico-deductive testing;
B) are supported by and based on many facts, experiments, and observations;
C) are broad, comprehensive and unifying statements (sometimes making use of insights from different disciplines);
D) explain *natural phenomena* (events, observations, relationships) or laws
E) ideally predict future observations;
F) are generally considered to have been invented rather than discovered.

Data

Each of the 15 current U.S. high school biology textbooks was reviewed with respect to the inclusion and definition of the terms "law" and "theory." The findings are illustrated in Table 3.

TABLE 3

Table 3. Use of the terms "theory" and "law" in current secondary school biology textbooks.

Text and Publication Date	Aspects of the definition of "law" provided in the texts See Table 1 for code	Aspects of the definition of "theory" provided in the texts. See Table 2 for code	Explicit examples of Laws and Theories provided in the text. See code below
1. Biggs (1998)	Example only, no specific definition	A, B, D, E	a, e, i, j
2. Biggs (2000)	Vague inclusion	A. B, D	a, i, j
3. Miller & Levine (2000)	None	A, C, D	a
4. Strauss & Lisowski (1998)	None	A, B, D	a, h, i, j

5. Strauss & Lisowski (2000)	None	A, B	a, h, i, j
6. Johnson & Raven (1996)	None	A, D	a, i, j
7. Johnson (1998)	None	C	i, j
8. Towle (1999)	None	A, C	a, e, i, j
9. Miller & Levine (2000)	None	B, E	a
10. Schraer & Stoltze (1999)	C	B, C	a, c, d, f, h, i, j
11. Johnson & Raven (2001)	None	A, B, C, D	a, g, i, j
12. BSCS (1998) *Ecological Approach*	None	D, E	a
13. BSCS (1997) *Human Approach*	None	A, B	a
14. Campbell, Reece & Mitchell (1999)	None	None	a, i, k
15. BSCS (2001) *Molecular Approach*	None	D, E	a, d, i

Specific examples of theories and laws included in the texts reviewed.

a. Cell theory
b. Germ theory
c. Law of probability with respect to genetic possibilities
d. Law of conservation of mass
e. Law of superposition
f. Law of use and disuse
g. Law of heredity
h. Law of dominance
i. Law of independent assortment
j. Law of segregation
k. Law of continuity

Results

These data suggest a depressing conclusion with respect to the portrayal and inclusion of laws and theories in secondary school biology textbooks. None of the books reviewed provides an acceptable view of either laws or theories yet a variety of concepts called theories and laws are included in these texts. It is clear that while the texts generally do a credible and engaging job discussing the concepts of biology, discussion of aspects of the philosophy of science in the life sciences is woefully lacking.

Laws

The textbook situation with respect to the term "law" is surprising. Most biology books include a range of examples of laws -- mostly from genetics. Yet, only one text includes any element of the definition of the concept and two others provide a discussion that is so vague as to be unhelpful. It may be that these authors believe that the scientific definition of the term "law" is well understood and is therefore not required, but that would likely be an unwise assumption. The limited range and similarity of biological laws provided as examples is also curious. Certainly, there are principles and laws in the life sciences beyond those in genetics, but most of the texts reviewed included the same ones. Some college level texts (not formally reviewed here) include mention of Allen's appendage and Bergman's body rules mentioned earlier and a few discuss Dollo's Law (the notion the structures lost through evolution cannot reappear in exactly the same form). Some texts include the principles of island biogeography related to species diversity, plot size and distance from a colonizing source. These laws established by Wilson and MacArthur are fascinating and would serve well to illustrate the properties of "lawness" to biology students. However, unless such concepts are called "laws" or principles there is no way that the typical student would appreciate the role played by such ideas in modern science.

Theories

The definition of "theory" adopted in this study has six parts. Using this measure, the range of completeness of the definitions provided ranges from zero to 66% complete. 60% of the books including something about validating theories by a cycle of testing and 53% say something about how theories are supported. Only 33% indicate that theories are broad unifying statements and 26% show that theories may predict future observations. None of the texts discuss the invention aspect of theory building. It is encouraging that over half of the texts reviewed featured a definition that includes a role for theories in explaining natural phenomena. If students and teachers are attentive to this distinction many of these books accurately describe the central role of theories, but the notion of theories as linking knowledge together in new and useful ways is all but absent.

A troubling issue is that almost every text includes "cell theory" as the sole named example of a biological theory. Unfortunately, while this idea does have some theory-like character in that it is comprised of postulates (i.e. all living things contain cells, the cell is the basic unit of structure and function and that all cells come from pre-existing cells), the case can be made that the cell "theory" is not a theory at all and is ultimately really more law-like in character. There is no final authority to help decide this case, but if one considers the explanatory and predictive roles played by the cell theory it is useful to ask the questions. What does the cell "theory" explain and what does it predict?

As typically stated, the cell "theory" can predict that the next as-yet-unstudied creature will have cells (because all living things contain cells) and explains why creatures have cells (again, because all living things contain cells). This is exactly the same way that laws not theories explain and predict. In contrast, the theory of evolution by natural selection uses its postulates and assumptions to explain *how* evolution occurs. This is quite different from the way that a law explains. For the moment we may be content to continue to refer to this notion as the cell "theory," while considering the possibility that a name change is in order. Interestingly, many biology texts designed for post secondary students have dropped the cell theory label and call this the cell principle instead.

Regrettably, several of the books include language about theories that is misleading. Strauss and Lisowski define a theory as a "hypothesis that is supported by many experiments done over a period of time . . ." (p. 1011). This is the long-discarded notion that hypotheses become theories and presumably with more evidence become laws (McComas, 1997). Fortunately, most of the texts may be faulted for the lack of comprehensiveness in the definitions provided rather than the incorrectness of those elements of the definitions that are included.

Implications

There is no sure way of knowing why confusion with respect to laws and theories exists but it is likely that two factors are responsible. First, there is the power of "common language" in which word meanings are transmitted, correctly or incorrectly, by the way they are applied generally in conversation. Frequently we hear that an idea is "*only* a theory," or that "I have a theory about that," or that "laws are meant to be broken." Such statements make no sense in science if the terms law and theory are used correctly.

Another source of confusion may relate to the shift in context when a term is used from one discipline to another. In mathematics, for instance, laws are defined by mathematicians rather than nature itself. Such laws are then applied with confidence because they are, by definition, universally true. The term "theory" in mathematics relates to a branch of study and the corresponding rules governing such study. In his history of mathematics, Eves (1983) lists scores of mathematical theories including those of classes, complex functions, equations, functions, groups, ideals, invariants, numbers, probability and sets. Students are to be forgiven if they fail to see the distinction between the way that terms are used in common language and in various disciplines but teachers should be more attentive to the potential for confusion.

The high degree of similarity with respect to the treatment of laws and theories in current biology textbooks is another interesting issue. For instance, why is it that almost every book includes examples of laws while at the same time failing to define the term? This state of affairs may have been explained by Gould (1988) who found a similar high degree of congruence in the example provided by countless biology books to illustrate the size of an ancient horse ancestor. Gould concluded that one author simply copied from previous books rather than considering the utility of the example in question. It is natural that authors would look at the competition before writing a new textbook or revising and old one, but rather than enhance their final product, authors seem content to make sure that their work is much the same as the others available. The majority of high school biology books present the same material in very similar ways. This is unfortunate because not only do the textbooks become increasing more similar and as such less potentially innovative, but omissions will go unaddressed and errors may remain uncorrected.

The findings reported here paint an unfortunate picture of the state of affairs with respect to two important issues in the nature of science. Laws and theories are among the most important tools and products of modern science and as such lie at the heart of understanding of how science functions. Unfortunately, these terms have meanings in common language quite distinct from the way they are used in science and the assumption on the part of textbook authors that students already know the meanings of these terms is not reasonable. It is vital that authors take more care to provide accurate and complete definitions coupled with useful examples as they endeavor to provide descriptions of how science functions just as they include accurate illustrations of the facts and concepts of modern biology.

Considering the dominant role played by textbooks in guiding biology instruction and in framing the curriculum, it is obvious that all important aspects of biology must be featured including content, process and the philosophy of biology. If textbooks contain incomplete or misleading information and if teachers lack firsthand ability to evaluate or add to the material in the text, it is likely that the current disappointing state of affairs with respect to nature of science education will be maintained. This analysis examined only theories and laws in biology texts, but the overwhelming negative findings suggest an equivalent problem with the entire nature of science domain. It would be useful to repeat this study for texts other science disciplines and/or for texts in use beyond the United States. Perhaps there will be some cases that will serve as successful examples of how to integrate important nature of science lessons into content rich settings.

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