Darwin's Theory, Mendel's Laws: Labels & the Teaching of Science

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"When the laws of inheritance ... became understood, that problem with Darwin's theory vanished. ..." (Raven & Johnson 1996).

"Darwin was led to the hypothesis of natural selection and ultimately to a broad evolutionary theory. That theory in turn, raised questions that led to research on the origin of variation, the laws of heredity, and the rates of evolutionary change" (Mix et al. 1996).

Introduction

These quotes illustrate a common practice in biology. We call Mendelian concepts "laws," but Darwinian concepts a "theory." Why? Both provide explanations of diverse observations in nature. Both have elements that are universal in biology. Both provide a fundamental basis to our understanding of modern biology. Nevertheless, we give them labels that can greatly affect our students' perceptions of their validity. Natural law connotes divine commandment, while theory connotes sheer speculation. Dictionary definitions support those connotations. For example, according to *The Oxford English Dictionary:* "The 'laws of nature', by those who first used the term in this sense, were viewed as commands imposed by the Deity upon matter, and even writers who do not accept this view often speak of them as 'obeyed' by the phenomena, or as agents by which the phenomena are produced." In contrast, one definition of theory in *The Oxford English Dictionary,* is: "A hypothesis proposed as an explanation; hence, a mere hypothesis, speculation, conjecture; an idea or set of ideas about something; an individual view or notion." This difference in labeling of Darwinian and Mendelian concepts led me to study biology textbooks in order to find out how biologists define and apply the terms law and theory. I soon found it necessary to study the use of hypothesis and principle as well.

In this paper, I will show that biologists disagree on some definitions and apply the terms inconsistently. I will also show that Darwinian concepts of evolution (change through time, common ancestry, natural selection) are about the only highly confirmed concepts in biology that are treated as theory instead of

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fact. Moreover, authors point out uncertainties and debates in evolutionary topics more than in many other areas of biology. I will propose reformulated definitions in an attempt to simplify and clarify them for students. I will argue that we should recognize, label, and treat many other biological concepts as theories, including Mendel's theories of segregation and independent assortment.

These findings are important because if evolution is the only topic we consistently describe as a theory and treat as uncertain, then students will understandably conclude that evolution is not real science. As one college senior put it in an angry evaluation of my evolution course, "Scientists don't study theories, they learn facts." Rutledge and Warden (2000) found that many teachers' understanding of evolution is weak, but the more they understood science, the more likely they were to accept evolution. By not teaching students that all unifying concepts in biology are theoretical in nature and incompletely understood at some level, we teachers may be fueling public misunderstanding of science in general, and evolution in particular.

Methods

My working assumption is that biology texts provide a reasonable sample of the ways we teachers represent theories, laws, hypotheses and principles to our students. I analyzed 12 introductory college biology textbooks, including some for biology majors and some for nonmajors (Table 1). If an author participated in writing several books, I chose only one to minimize the influence of any one author on this study. I did not attempt to evaluate any book, so readers should not infer from my comments or quotes that some books are better than others.

I analyzed the texts in five different ways for definitions and examples of the terms hypothesis, theory, principle and law. First, I located definitions of those terms in the glossary and in the text. Second, I found where the terms were discussed in the text, usually Chapter 1 or 2, and I noted all the examples given. Third, I looked in the indices for all concepts associated with those terms. Fourth, I looked in the detailed tables of contents for all headings containing the four terms. Finally, since those methods did not locate all theories and hypotheses, I analyzed how authors talked about a sample of theoretical concepts. I chose 20 concepts that varied in breadth and certainty, and that represented a broad spectrum of biology (Table 2). I noted whether the authors talked about each concept as hypothesis, theory, principle or law.

I also used those 20 concepts to analyze how authors talked about theoretical concepts that vary in degree of certainty. I noted whether each concept was described as fact or as provisional understanding. Then I counted all explicit statements of uncertainty. One expression of uncertainty is an "unanswered question," where a question is posed indicating that scientists do not know the answer at present.

Table 1.

	Hypotheses explain specific events.	Hypotheses are weakly supported theories.	Theories are broad in scope (B), or explain sets of observations. (S)	Theories are strongly supported.	Laws are theories with highest support.
Audesirk & Audesirk 1996		X		X	X
Campbell et al. 1997	X		B	X	—
Ferl & Wallace 1996	X	X	S	X	X
Gould & Keeton 1996		X		X	—
Lewis 1998	X		S		—
Mix et al. 1996		X	B	X	X
Postlethwait & Hopson 1995	X		B		—
Purves et al. 1998		X	—	X	—
Raven & Johnson 1996		X		X	—
Solomon & Berg 1995		X	S	X	X
Starr & Taggart 1998	X		B	X	—
Tobin & Dusheck 1998	X		S	X	—

Comparison of views of hypothesis, theory and law in definitions and explanations of those terms in 12 biology textbooks. A dash (—) means authors do not define the term. Principle is not included, because only one book defined it.

Table 2.

Theoretical concepts analyzed in the 12 biology textbooks, including the sections of text not analyzed.

- Enzyme function by induced fit and other mechanisms, but not activation energy, equilibria or coenzymes.
- Plasma membrane structure, but not transport mechanisms, or structure of particular proteins.
- Chemiosmosis.
- Cell cycle control mechanisms, but not descriptions of the cycle or cell division.
- Operon mechanism, but not protein synthesis.
- Eukaryotic gene expression control processes, but not protein synthesis.
- Inheritance mechanisms, including Mendelian, non-Mendelian, and human genetics, but not ethics, human genome project, gene therapy or cancer.
- Developmental control processes, but not description of development or postembryonic processes.
- Clonal selection mechanism, but not other aspects of the immune response.
- Self-nonself recognition mechanisms, but not autoimmune disease.
- Sodium-potassium pump mechanism of resting and action potentials, but not saltatory conduction or synapse transmission.
- Sliding filament mechanism of muscle contraction, but not control processes, summation or tetany.
- Calcium mechanism for stimulating muscle contraction.
- Stomata control mechanisms.
- Xylem transport mechanisms.
- Phloem transport mechanisms.
- Diversity-stability relationship in ecological communities.
- Human causation of global warming, but not possible future effects.
- Human causation of stratospheric ozone depletion, but not possible future effects.
- Evolution, including introductory chapters of the books, history of the concept, evidence, population genetics, adaptation, speciation, macroevolutionary processes, and classification, but not continental drift, or history of life chapters.

I disregarded rhetorical questions and questions that authors posed, then answered. Another way to express uncertainty is to point out a contemporary disagreement over some part of the concept. For a passage to count as "debated," the authors had to say explicitly that there is a contemporary debate, a controversy, or at least "some say X, but others say Y." Finally, there were miscellaneous other ways that authors could express explicit uncertainties. Examples are: "We don't understand why" or "The mechanism is unknown."

I read all 20 sections in each textbook at least twice to check my scoring. The uncertainties had to be relevant to the concept I was examining. For example, if I was studying how authors talked about the mechanism of chemiosmosis, I did not score their uncertainty about how it evolved. Likewise, if the question was whether humans cause global warming or the ozone hole, I did not score uncertainties expressed in the prediction of the future effects of these phenomena, unless authors pointed out a scientific disagreement. The uncertainties had to pertain to views of knowledgeable scientists. Thus, I disregarded creationists' problems with evolution. Finally, I did not count implicit uncertainties, unless they were emphasized by the context. Examples of implicit uncertainties are: "According to the X hypothesis," "It may be that," "It seems that," "Apparently," "This suggests that," "The X hypothesis explains," and "There is good evidence that." In my experience, most students do not read uncertainty into those phrases.

Some topics occupy more space in a textbook than others do. Thus, I estimated the number of uncertainties per page. In counting pages, I omitted chapter summaries because they might duplicate uncertainties already scored. I omitted box inserts if they did not address the concept I was studying. For most topics, I did not count the space occupied by introductory paragraphs and illustrations that had no explanatory content, but for three topics that covered many pages, that was not feasible. Thus, for evolution, inheritance and development, the page numbers are overestimated and the average uncertainties per page are slightly underestimated compared to the other topics.

Results

Hypotheses

All of the biology textbooks say that hypotheses are tentative, uncertain explanations that must be testable. However, there does not seem to be unanimity on the breadth of hypotheses. Six textbooks say (or imply by examples in introductory chapters) that hypotheses are specific explanations for an observation, an event, or a single phenomenon (Table 1). Seven specify that hypotheses are less certain versions of theories, which would mean that they are not necessarily so specific.

If we look at examples of hypotheses outside the introductory chapters, we see that authors in the "specific explanation" camp all attach the hypothesis label to more general explanations not tied to specific observations or experiments. Examples are the explanation of phloem transport (3 of the 6 books), speciation mechanisms (2 of 6), xylem transport mechanisms (1), numerous neutral alleles in species' genomes (1), diversity/stability in communities (1), clonal selection (1), chemiosmosis (1), sliding filament muscle contraction (1), adaptation by step-wise accumulation of mutations (1), and natural selection (1). In the "uncertain theory" group, we also see a range of examples from very specific (e.g., explanations for why the car won't start and whether ginkgo trees have an internal clock) to fairly broad concepts (e.g., morphogens in development, speciation, phloem transport, blending inheritance, punctuated equilibrium, natural selection).

Theories: Scope

Four books specify that theories have a broad scope (Table 1). Their examples in Chapters 1 or 2 were universal: theory of evolution, theory of natural selection, cell theory. But in other chapters the books cite less universal concepts, such as chemiosmosis, xylem and phloem transport mechanisms in vascular plants, clonal selection theory in the vertebrate immune system, and endosymbiosis (Campbell et al. 1997; Starr & Taggart 1998; Mix et al. 1996). Of the remaining eight books, half say that theories explain or relate classes of phenomena or a variety of facts; half give no indication of theory breadth. Presumably authors of those eight books allow that a concept need not be extremely broad to be called a theory. Their examples of theories include estrogen mimicry of environmental pollutants, bacterial cause of peptic ulcers, sliding filament muscle contraction, the morphogen concept of development, impact cause of dinosaur extinction, and self-nonself recognition by the immune system.

Theories: Confidence

Most textbooks (8 of 11) define theories as unifying explanations that have withstood repeated and rigorous testing and thus are well confirmed. Five of those specify, and one implies, that theories are strongly supported hypotheses. Only Lewis (1998) and Mix et al. (1996) allow the possibility that unifying explanations could be called theories before they have amassed much support. There are indeed some very highly confirmed concepts that books refer to as theories (theory of evolution, occasionally cell theory or chromosome theory), but books often imply in the following ways that theories are not always highly confirmed.

First, not all concepts labeled as theories are highly supported concepts. For example, authors who maintain that theories are very well confirmed refer to the following as theories: mechanisms of xylem transport (in 4 of the 8 books), phloem transport (3 books), punctuated equilibrium (2), explanations of mass extinction (1), red queen explanation for sex (1), pattern formation in development (1), good genes explanation for female choice (1), response to danger as the immune system's mechanism of recognizing self versus nonself (1). Other books may mention uncertainties in those concepts or treat them as hypotheses, suggesting that those concepts are not highly confirmed. Occasionally, an author's language will reveal an awareness that theories are not always well confirmed, despite their definition. Here is an example: "Researchers speculated that the twins learned to recognize each other's cells as self while they were in the womb together. To test this theory, English biologist Peter Medawar showed that he could 'teach' newborn mice to tolerate foreign cells" (Tobin & Dusheck 1998, p. 861). Sometimes authors even label discredited concepts as theories: blending inheritance (in 3 of the 8 "strong-support" books), Lamarckian evolution (3 books), spontaneous generation (1), Cuvier's catastrophism (1), preformation (1), and the "scriptural theory of creation" (1). In only one case was there a hint that these should not be called theories.

Second, the theory label may be applied to a concept only when it is new. Some authors refer to a concept as a theory in a historical discussion, but not in the rest of the chapter where the concept is explained, for example, Mendelian concepts (3 books), chromosomal inheritance (1), Wolpert's morphogen concept of development (1), the Burnet and Medawar concept of self-nonself recognition (1), the sliding filament mechanism of muscle contraction (1). Again, the context may make it clear that those early theories were not well supported. Several examples are: "Satisfying as it was, this template theory of DNA replication was pure speculation when first put forward by Watson and Crick" (Gould & Keeton 1996) and "The theory of blending scarcely explained the obvious variation in traits that people could observe with their own eyes" (Starr & Taggart 1998).

Third, theory and hypothesis may be used synonymously. Sometimes both terms are applied to an idea in the same historical discussion: Mendel's ideas (2 books), Lamarck's inheritance of acquired characteristics (2), Darwin's ideas (1), Wolpert's morphogen concept (1), and clonal selection (1). Some books used the labels interchangeably in discussing contemporary issues: the red queen explanation for sex, impact explanation for extinctions, and phloem transport mechanisms (1 book each). Sometimes authors call an idea a hypothesis in a historical context, but a theory in a contemporary context: Darwinian ideas (6 books), xylem transport mechanisms (2 books), and clonal selection (1). It took me a while to realize that some authors were using one term when describing the history of a concept and another when talking about contemporary understanding. The distinctions are always implicit and subtle, so I doubt many students ever realize what the authors are doing. Since students understand "hypotheses" are provisional, using hypothesis and theory for the same concept gives the impression of uncertainty to theories. Interestingly, in three books Mendel's original theory graduates to a law, while in six books, Darwin's original hypothesis graduates to a theory.

Fourth, most highly confirmed unifying concepts are not called theories. Only one text in 12 speaks contemporaneously about the theory of independent assortment and the theory of segregation of

Table 3.

	Concept has unanswered questions.	Scientists disagreed about some aspects.	Other expressions of uncertainty.	Total explicit uncertainties per page.	Percent of books with any explicit uncertainty.	Percent of texts calling present knowledge a theory.
Evolution/natural selection	7	41	121	0.26	100%	92%
Developmental control	13	1	12	0.43	70%	9%
Eukaryotic gene regulation	3	1	10	0.43	64%	0%
Stomata control	0	1	5	0.80	45%	0%
Human cause of global warming	0	3	6	0.59	42%	0%
Cell cycle controls	0	0	3	0.28	38%	0%
Inheritance	6	1	14	0.05	33%	8%
Chemiosmosis	0	1	2	0.14	17%	33%
Human cause of ozone hole	0	1	2	0.34	17%	0%
Calcium stimulation of muscles	0	0	1	0.12	11%	0%
Xylem transport	0	0	1	0.06	9%	45%
Clonal selection	0	0	2	0.12	8%	42%
Sodium-potassium pump	0	0	1	0.03	8%	0%
Operon mechanism	1	0	0	0.03	8%	0%
Sliding filament contraction	0	0	1	0.05	8%	0%
Diversity-stability	0	0	0	0.00	0%	0%
Enzyme mechanisms	0	0	0	0.00	0%	0%
Plasma membrane structure	0	0	0	0.00	0%	0%
Phloem transport	0	0	0	0.00	0%	30%
Self-nonself recognition	0	0	0	0.00	0%	0%

Explicit uncertainties expressed in discussions of 20 explanatory concepts in biology. Uncertainties include times that authors acknowledge that not everything about the topic is known and times that authors mention a difference of views among scientists. The number of uncertainties per page is the total of the three uncertainty columns divided by an estimate of the total pages devoted to that topic in all 12 books. Percent means percent of books that discuss the topic.

alleles; in the rest, they are Mendel's laws or principles. When explaining present knowledge, all books describe the fluid mosaic membrane, induced fit enzyme function, the sodium/potassium pump, operons, sliding filament muscle contraction, and self-nonself recognition by the immune system in a matter-of-fact, "this is the way it is" kind of language. When discussing our present understanding of these topics, authors rarely express any uncertainty, but none call them theories (Table 3). Usually authors attach no labels at all to such well-established explanations or descriptions of processes. Some may refer to certain concepts as "models," but discuss those models as unequivocal facts. In contrast, when discussing present knowledge of evolutionary biology, all but Lewis (1998) refer to Darwinian concepts of evolution as theory, and at an average rate of 10 times per evolution section (the parts listed in Table 2, minus the history of the concept).

Finally, the language used to discuss evolution places it among the most uncertain of biological concepts (Table 3). Although authors present the evidence for evolution at some length, evolutionary topics may not be discussed in the same matter-of-fact way that many other topics are discussed. For example, 11 of the 12 books pointed out debates among scientists over evolutionary ideas. They mentioned evolutionary debates four times more than debates in 19 other topics combined (Table 3). Moreover, authors often heighten the disagreement with emphasizing modifiers like "hotly debated," "debates still rage," "great deal of argument," or "highly controversial." The expressions of uncertainty are generally about the operation of certain components of evolution, rather than whether common ancestry, natural selection, or speciation occur. However, texts do not present students the incompletely understood components of most other biological concepts (Table 3). When they do, the language is bland. Rarely do they even use the words debate or controversy.

Law

All books use the term law, but only four define it. In each definition, a law is a theory or hypothesis with the highest level of confidence, or a "fact" short of absolute certainty. One book also stipulates that the theory be of "great basic importance" (Solomon & Berg 1995).

Most often, authors cited examples from physics, such as the laws of thermodynamics. Table 4 shows all their examples of biological laws. Most commonly cited were Mendel's segregation of alleles and independent assortment. They occasionally cited Hardy-Weinberg equilibrium and three general ecological patterns. Curiously, two texts listed Lamarck's discredited use and disuse concept as a law.

Principle

Principle is a label used by 6 of the 12 books, but only one defines it: "A theory that, over a long period of time, has yielded true predictions and is thus almost universally accepted ..." (Solomon & Berg 1995). Principle then becomes equivalent to some authors' definitions of theory and equivalent to other definitions of law.

Table 4 shows the concepts labeled as principles in the 12 biology textbooks. Three books use "Mendel's laws" and "Mendel's principles" interchangeably. Three books use "Mendel's principles" instead of "Mendel's laws." Five of the books refer to common ancestry, change through time, or natural selection as principles a total of 8 times, while referring to "the theory of evolution" 60 times. Also, they avoid using "the principle of evolution" as a label. Postlethwait and Hopson (1995) speak of "the principle of natural selection," then conclude with "Evolution by natural selection is so grand an organizing principle for all biology ..." Audesirk and Audesirk (1996) title a chapter "Principles of Evolution," but in the text, they only talk about the theory of evolution or the theory of natural selection. In short, while books may use the term principle in discussions of Mendel and Darwin, for Mendel it is a formal label equivalent to law; for Darwin it is not.

Summary

This study of textbooks reveals that biologists use different definitions of hypothesis, theory, law and principle. It shows that our examples may not always reflect our definitions.

All textbooks agree that hypotheses are tentative testable explanations. However, they seem to represent them in two ways. Some represent them as narrow and tied to particular studies or experiments. Some talk of hypotheses as explanations or generalizations of a body of work and may make no distinction between hypotheses and theories other than degree of support.

A theory is also a description or explanation of patterns or processes observed in nature, but we generally do not apply the term to explanations of specific observations or tests. Rather, authors agree that theories attempt to catalog and explain results and observations from a variety of sources, or related sets or sys-

Table 4.

	Theory	Law	Principle
Evolution (including selection)	(8)11	0	5
Life composed of cells	(2) 5	0	0
Chromosomes carry genes	2	0	0
Xylem transport mechanism	2	0	0
Phloem transport mechanism	2	0	0
Lamarck's inheritance of acquired characters	3	0	0
Endosymbiotic origin of organelles	2	0	0
Spontaneous generation	(1) 1	0	0
Germs cause disease	(1) 1	0	0
Pattern formation in embryos	1	0	0
Island biogeography	1	0	0
Estrogen mimicry of environmental pollutants	(1) 1	0	0
Cuvier's catastrophism	1	0	0
Bacterial cause of peptic ulcers	(1) 1	0	0
Self-nonself recognition of the immune system	1	0	0
Mendelian independent assortment and segregation	1	(1) 7	6
Hardy-Weinberg	0	(1) 3	2
Lamarck's use and disuse	0	2	0
Liebig's minimum limiting factor	0	2	0
Shelford's ranges of toleration	0	2	0
Merriam's temperature control of distribution	0	1	0
Biogenesis	0	(1) 1	0
Fick's equation of diffusion in gas exchange	0	1	0
Competitive exclusion	0	0	3
Griffith's transformation of bacteria	0	0	2
Colinearity of DNA and RNA codons	0	0	1

Examples of biological theories, laws and principles from college level introductory biology textbooks. The numbers tell how many books, out of 12, that apply a particular label to a particular concept in the glossary, index, headings of the table of contents, or introductory chapters. In parentheses are the numbers of books that cite these examples in the introductory chapters, where the labels are defined. The total across rows is greater than 12 for Mendelian concepts and evolution, because some books apply two different labels.

tems of data. Beyond that, multiple definitions and inconsistent labeling of concepts muddy the other characteristics of theories. Some specify that theories are broad in scope. Broad can mean different things to different people, but given the examples in the textbooks, we can conclude that a theory does not have to be universal, or even nearly so. Thus, many unifying constructs in biology that are less universal than evolution can be called theories (Tables 2 & 5). Some biologists specify that theories are strongly supported. Analysis of biology textbooks reveals that on one hand some concepts we call theories are not well supported. On the other hand, many well-supported concepts are simply not called theories. When a concept becomes generally accepted, we drop the label and treat it as fact, except for the "theory of evolution" and occasionally a few others.

The few texts that define laws seem to agree that laws are well-confirmed theories that are not likely to change; they are facts of nature. Thus, laws are a subset of theories, and well-confirmed theories are facts.

Biology texts use the word principle in the same sense as law.

Thus we see that concept labeling in biology is inconsistent. One reason for the inconsistency is the way "scientists have labeled their own work. Mendel and Lamarck called their ideas laws, while Darwin called his ideas theory. Another factor is tradition. Generations of academics have been taught the "theory of evolution" ,and "Mendel's Laws" and we use these ingrained phrases without thinking of their implications.

A final summary point is that most textbooks treat evolution differently from other unifying concepts. They continue to label evolution as a

Table 5.

PHYSIOLOGY
- Cell theory
- Theories of chromosome migration
- Cellular receptor theory
- Theories of hormone control of cell activity
- Enzyme kinetics theory
- Photosynthesis theory
- Cellular respiration theory
- Contractile ring theory
- Homeostasis theory
- Theory of chemical signaling between pollen & ovary
- Heartbeat regulation theory
- Blood circulation theories (vertebrate, invertebrate)
- Theories of digestion
- Pulmonary gas exchange theory

GENETICS
- Germ line theory
- Double helix theory of DNA structure
- Chromosome (DNA) theory of inheritance
- Chromosome theory of sex determination
- Mutation theories
- Central theory of molecular biology
- Kinetic molecular theory
- Structure/function complementarity theory

DEVELOPMENT
- Theory of development as a series of one-way switches
- Programmed cell death theory
- Mosaic theory vs. regulative development theory
- Pattern formation theory
- Developmental fields theory
- Aging theories

IMMUNE SYSTEM
- Theory of acquired immunity
- Neo-natal immuno-tolerance theory
- Autoimmunity theory

DISEASE
- Germ theory
- Stress and microbial theories of peptic ulcers
- Theories of arterial plaque formation
- Theory of Type 1 and Type 2 diabetes
- Theories of cancer development

ECOLOGY
- Niche theory
- Population regulation theories
- Competition theory
- Patch dynamics theory
- Island biogeography theory
- Community structure theory
- Community succession theory
- Community continuum theory vs. individual distribution theory
- Keystone species theory
- Edge effect theory
- Nutrient cycling theory
- Acid precipitation theory
- Balance of nature theory
- Gaia theory

A sampling of nonevolutionary biological theories. Some were proposed by participants in workshops on teaching of science at Radford University and University of Oregon before anyone presented the ideas in this paper. I added others. Table 2 lists additional theories. These do not constitute a definitive list. Some large parts of biology are not included because we did not have participants representing those areas.

theory, while other well-established concepts are treated as facts or labeled as laws. Evolution was the only one of 20 concepts where each of the 12 textbooks explicitly pointed out uncertainties. Authors commonly emphasized scientific debates in evolutionary biology, but rarely even mentioned disagreements over other concepts.

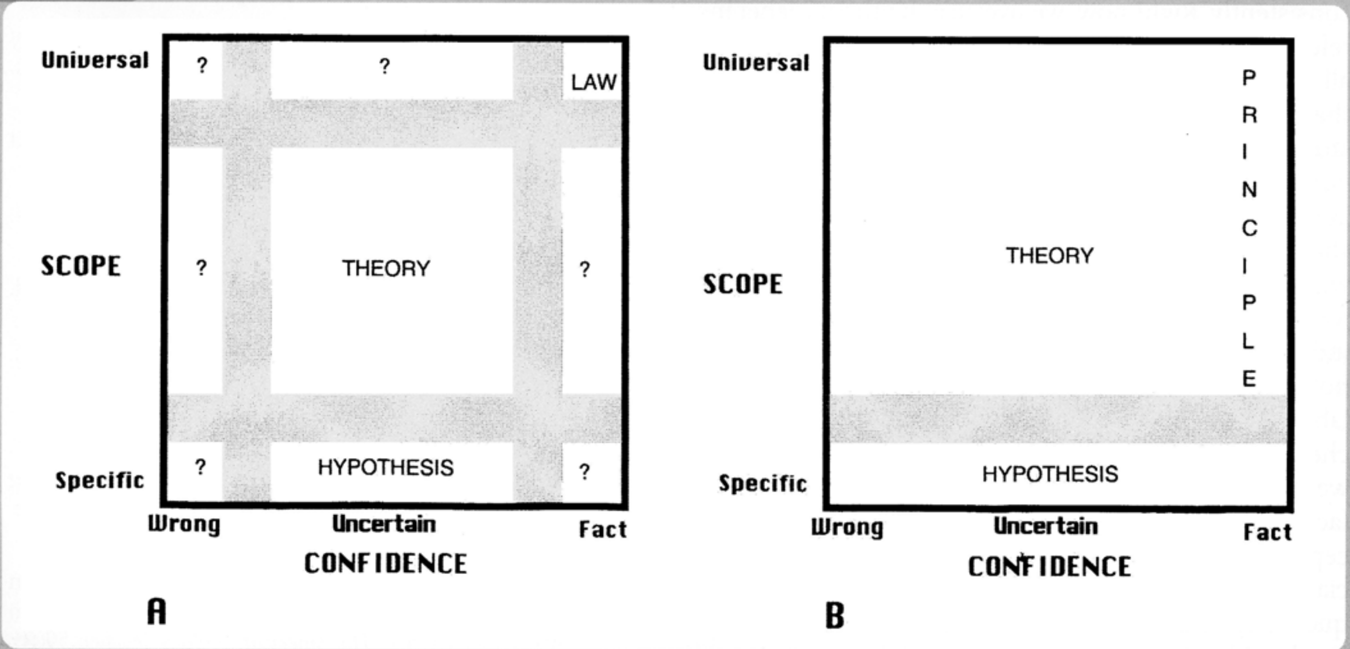
Recommendations

I will attempt to clarify terms in a way that reflects the processes of science and the examples seen in the textbooks. My investigations revealed that hypotheses, theories and laws (or principles) sort out along two dimensions in biology texts: scope and degree of confirmation (or our confidence in them). We can represent these views graphically (Figure 1) to see how our terminology might cover the range of concepts. In Figure 1A the Y-axis distinguishes hypotheses of particular studies from explanations of sets of data and universal concepts. On the X-axis it distinguishes speculative ideas from disproved ideas on one hand and from highly confirmed concepts on the other. This framework could discriminate hypothesis, theory and law (though some authors would disagree about where I have placed those terms). However there are a number of problems. There are more boxes than we have terms. There are 12 boundaries between adjacent boxes, where decisions about classifying a concept will be difficult and contentious (shown as gray areas). Finally, according to some biologists, laws are not simply well-confirmed theories. Laws, they say, are descriptions of patterns in nature, while theories are explanations of the causes of those patterns (National Academy of Sciences 1998; McComas 1997). I did not see such a distinction in any of the biology texts, but that view seemed implicit in 4 of the 9 college physics and chemistry textbooks I examined. Also, one can see the distinction in philosophical treatises, which tend to be heavily influenced by the physical sciences (e.g., Campbell 1952; Hempel 1966; Nagel 1961).

My proposal in Figure 1B has fewer gray areas where labeling will be difficult. In this view, hypotheses are propositions that guide the study of particular situations. Theories are unifying scientific explanations or general descriptions of sets of observations. Theories vary widely in confidence and scope (in accord with dictionary definitions and the examples we see in textbooks). This allows us to call new and established theories by the same label, instead of switching from hypothesis to theory. Also, we do not have to change the label again if the theory is discarded. Instead of label swapping, we can speak of a new (or speculative) theory, a currently developing theory, a reformulated theory, an established (or well-supported) theory, and a discarded theory. Referring to theories with adjectives like these more clearly shows students the process of science and reminds them that all ideas in science are subject to change and refinement. Both theory and hypothesis should be applied only to testable scientific explanations that do not posit supernatural forces and are tested with repeatable natural observations (thus, creationist beliefs are not theories). If a hypothesis or a theory becomes highly confirmed, then we could drop the labels and simply treat them as facts, as we do for most concepts already. If we want to emphasize the certainty of the concept and think a label is necessary, then we could use a neutral term like principle. Principles do not have their own box in Figure 1B because they are actually theories. Though no gray area is shown, I would expect disagreement over when to apply the term.

The distinction between descriptive laws and explanatory theories has heuristic value, and is probably necessary for historians and philosophers of science. However, that distinction is problematic in biology teaching. To be consistent, we would have to label many things we talk about as laws. For example, we would teach the theory of descent with modification, but law of fundamental unity of life, the law of change through time, the law of proximity of similar species in geologic columns, and Darwin's laws of biogeography. Harvey's theory of circulation would become the law of closed circulation and the theory of circulation (mechanisms that cause blood movement). It will not always be obvious whether something is a law or a theory (Nagel 1961). For example, McComas (1996) calls Newton's concept of gravity a law; Dilworth (1996) and Trusted (1979) call it a theory. Are segregation and independent assortment laws or theories, or both? Finally, there is the potential for misinterpretation. Law carries the legal connotation of a rule to follow and the religious connotation of divine commandment. Indeed, early scientists meant God's rules (Giere 1984). But in reality, descriptions of patterns or rela-

Figure 1.



Possible schematic representations of the relationships among hypotheses, theories, and laws or principles. Gray areas represent boundaries in which decisions about how to classify a particular concept will be difficult. Further explained in the text.

tionships in nature are human proposals based on potentially flawed human perceptions. They can be tested. They can increase or decrease in scope and confidence. They can be discarded. In other words, laws could be considered descriptive theories. Thus, I avoid talking about laws with students, even when discussing gravity or thermodynamics. We can just as well speak of Newton's theory of gravity and Mendel's theory of independent assortment. Using the word theory emphasizes that these are all human attempts to make sense of human observations.

A full analysis of ways to define hypothesis, theory, law and principle is beyond the scope of this paper. Instead, I present these thoughts to stimulate discussion and I am perfectly willing to consider alternatives. I caution, however, against expecting the simple graphs in Figure 1 to represent the complex processes of science fully. As a theory is tested, its position along axes of confidence or scope will change through time. Moreover, the theory itself changes. A hypothesis may become part of narrow theory, which may be a component of a more inclusive theory. A theory may change in confidence, but not scope, and vice versa. Any theory may have some speculative parts and other highly confirmed parts; some narrower components and some broader components. Therefore, it may be futile to try to locate any particular theory at any particular point on the diagram. Nevertheless, the diagrams may provide a conceptual framework for choosing labels that allow for these processes of science.

Whatever the definitions, we need to apply them consistently. Right now, we overuse the theory label in referring to evolution, while we don't use the label at all in referring to scores of other biological theories that we simply treat as facts. That sends the message to students that evolution is speculation, while all else is fact. This has to change. After reading this article, if people still want to teach Mendel's laws, then they should also teach Darwin's laws. On the other hand, if we speak of Darwin's theory of natural selection, then we must speak of Mendel's theory of segregation, the induced fit theory of enzymes, the theory of action potentials, and digestion theory. If we drop the theory label for generally accepted concepts like operons, chemiosmosis, and the sodium-potassium pump, then we should drop the label and use the same matter-of-fact rhetoric with well-established evolutionary concepts like common ancestry, natural selection and speciation. If we point out the uncertainties, remaining questions and debates in evolutionary biology, then we should point out uncertainties and debates in every other facet of biology, for example, uncertainties in cellular respiration theory, debates in immune system theory, and remaining questions about how enzymes function. We can decide individually how to make our language consistent, without waiting for consensus on definitions of labels or waiting for textbooks to change. We can start today.

My preference is to tell students about all the theories in biology and, as much as possible, the remaining questions. We must show students (and let them practice) the processes of science – debates over alternative explanations of data, changing theories, remaining questions – in all areas of biology. If we do that in all courses, perhaps students will see that science is more about studying theories than memorizing facts. Eventually, maybe the public will understand that the study of evolution is normal science.

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