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Author(s): Sandra D. Mitchell
Reviewed work(s):
Source: *Philosophy of Science*, Vol. 67, No. 2 (Jun., 2000), pp. 242-265
Published by: The University of Chicago Press on behalf of the Philosophy of Science Association
Stable URL: http://www.jstor.org/stable/188723

Dimensions of Scientific Law*

Sandra D. Mitchell†‡
History and Philosophy of Science, University of Pittsburgh

Biological knowledge does not fit the image of science that philosophers have developed. Many argue that biology has no laws. Here I criticize standard normative accounts of law and defend an alternative, pragmatic approach. I argue that a multidimensional conceptual framework should replace the standard dichotomous law/accident distinction in order to display important differences in the kinds of causal structure found in nature and the corresponding scientific representations of those structures. To this end I explore the dimensions of stability, strength, and degree of abstraction that characterize the variety of scientific knowledge claims found in biology and other sciences.

1. Introduction. Biological knowledge does not appear to fit the image of science that philosophers have developed. In particular it has long been argued that biology has no laws (Smart 1968, Beatty 1995). Yet, biologists speak of "laws" in their writings. One of Mendel's "laws" claims that with respect to each pair of alleles at a locus on the chromosome of a sexual organism, 50% of the organism's gametes will carry one representative of that pair, and 50% will carry the other representative of the pair. Recently, a number of biological scaling "laws" have been discovered. These include Kleiber's Law that metabolism increases in proportion to body mass raised to the 3/4 power, and the scaling law that respiratory rate is in-

*Received July 1999; revised October 1999.

†Send requests for reprints to the author, Department of History and Philosophy of Science, University of Pittsburgh, 1017 Cathedral of Learing, Pittsburgh, PA 15260.

‡The research for this paper was supported by National Science Foundation. Science and Technology Studies Program. Grant No. 9710615. An earlier version was read at the American Philosophical Association, Eastern Division Meetings, December 1998. I wish to thank Joel M. Smith for inspiring criticisms and suggestions, Michael Weisberg for able research assistance, and Peter Machamer, Nancy Cartwright, and the two referees for insightful comments.

Philosophy of Science, 67 (June 2000) pp. 242–265. 0031-8248/2000/6702-0007$2.00

versely proportional to body mass raised to the 1/4 power (West et al. 1997, Pool 1997).

Why do some philosophers fail to count these results of biological investigation as laws? How are they different from Proust's law of definite proportion or Galileo's law of free fall or the conservation of mass-energy law? Those who argue that there are no laws in biology point to the historical contingency of biological structures and the particularity of the referents in biological generalizations as grounds for excluding the law designation. In considering the problem of the existence of biological laws I was led to a general reflection on laws in science. My conclusion is that we need to think about scientific laws in a very different way: to recognize a multidimensional framework in which knowledge claims may be located and to use this more complex framework to explore the variety of epistemic practices that constitute science. In this paper, I will argue that dichotomous oppositions like "law vs. accident" and "necessity vs. contingency" produce an impoverished conceptual framework that obscures much interesting variation in both the types of causal structures studied by the sciences and the types of representations used by scientists. As I will argue, causal structures vary with respect to both stability and strength while our representations of those structures concurrently span a range of degrees of abstraction, simplicity, and cognitive manageability.

I take this project to be similar in spirit to Carnap's analysis of the acceptance of different linguistic forms within science. He concludes his investigation of the relative worth of using thing language, abstract language, or not speaking at all:

> The acceptance or rejection of abstract linguistic forms, just as the acceptance or rejection of any other linguistic forms in any branch of science, will finally be decided by their efficiency as instruments, the ratio of the results achieved to the amount and complexity of the efforts required. To decree dogmatic prohibitions of certain linguistic forms instead of testing them by their success or failure in practical use is worse than futile; it is positively harmful because it may obstruct scientific progress. The history of science shows examples of such prohibitions based on prejudices deriving from religious, mythological, metaphysical, or other irrational sources, which slowed up the developments for shorter or longer periods of time. Let us learn from the lessons of history. Let us grant to those who work in any special field of investigation the freedom to use any form of expression which seems useful to them; the work in the field will sooner or later lead to the elimination of those forms which have no useful function. Let us be cautious in making assertions and critical in examining them, but tolerant in permitting linguistic forms. (Carnap 1950)

I endorse both Carnap's pragmatic standard and his plea for toleration. However, I believe it should be applied not only to linguistic expressions within science but also to philosophical expressions about science.

In addressing generalizations used in science, should we talk exclusively in terms of laws and accidents? Should we talk solely in terms of necessity and contingency? Should we represent the type of generality of scientific knowledge only in terms of the universal operator in first order predicate calculus? Representational forms and particular representations are simultaneously illuminating and limiting. They cannot perfectly represent their objects because they do not display *all* the features of the thing represented. Therefore, they must be judged, at least in part, in terms of their usefulness. In defending a multidimensional account of scientific knowledge I will expose limitations of traditional philosophical analyses and representations of knowledge of causal structures in nature in the hopes of showing how a different sort of enterprise promises to be better for understanding the diversity of scientific practices.

In examining the question of the nature of scientific laws and the existence or nonexistence of laws in biology, it is useful to ask first what options are available for approaching the problem. Before we can decide if biology has laws or if any claim of knowledge about the world is a law, we need to be clear what a law is and what the candidate claims look like.

2. Normative and Pragmatic Strategies. In Mitchell 1997 I suggested three strategies for investigating the question of the existence of laws in biology: a normative, a paradigmatic, and a pragmatic approach.

> The normative approach is the most familiar. To proceed, one begins with a norm or *definition* of lawfulness and then each candidate generalization in biology is reviewed to see if the specified conditions are met. If yes, then there are laws in biology, if not, then there are no laws in biology. The paradigmatic approach begins with a set of *exemplars* of laws (characteristically in physics) and compares these to the generalizations of biology. Again, if a match is found, then biology is deemed lawful. The pragmatic approach focuses on the *role* of laws in science, and queries biological generalizations to see whether and to what degree they function in that role. (Mitchell 1997, S469)

In this paper I will further develop those ideas. I will elaborate the normative approach, articulating both its features and its foibles. I will then argue in favor of a pragmatic approach that focuses on the function of laws and holds that there are a variety of forms of scientific claims that provide us with usable knowledge. I will show that the pragmatic strategy leads us to develop a multidimensional framework of features that characterize useful scientific generalizations. I will argue that only by substituting this analytical framework for the standard dichotomous law/accident talk do we adequately represent the complexities of good scientific practice.

3. Traditional Normative Approaches. Consideration of what counts as a law of nature and corresponding implications for the variety of claims generated in the many sciences continues to be dominated by normative approaches. That is, one begins with a *definition* of lawfulness that constitutes the standard by which scientific claims are judged. Among the normativists, the largest divide is between empiricists (of naive or sophisticated sorts) who claim that laws are just true generalizations describing the regular events occurring in nature and necessitarians who claim that laws explain why those events, and not others, obtain. For empiricists, patterns of events constitute laws while for necessitarians it is the laws that "govern" which events occur (Dretske 1977, Earman 1984). In both cases the identifying characteristics for what qualifies as a *law* are some notion of generality or universality and some notion of necessity. After all, we use laws to tell us about what happens outside the confines of our finite experience. As Richard Feynman (1995, 164) puts it, "Science is only useful if it tells you about some experiment that has not been done; it is no good if it only tells you what just went on. It is necessary to extend the ideas beyond where they have been tested." Generality has been standardly symbolized by universality in the logical sense—that is the kind of generality that can be represented as (x) in a statement of law $(x)(Px \rightarrow Qx)$. Necessity is often identified with an ability to "support" counterfactual claims. Knowledge of laws is meant to allow us to predict and explain particular events and hence successfully intervene in our world.

For empiricists this means knowing what the world of events is like, what follows what. Laws are the best summary of those facts. For necessitarians laws express relations that explain the facts. Necessitarian laws proscribe, not just describe, the events that occur in our world. To accomplish that, necessitarians require laws to be more than just a record of what is true but rather a description of what must be true. Thus, for them, universality and truth, are insufficient. On the basis of universal truths, we could predict what would occur for all time, but there is still a worry about explanation. Some universal truths are taken to be merely accidental and thus incapable of explaining why one event occurred by failing to preclude other possible events that could have occurred in its stead. To have an explanation, it is suggested, one needs to have knowledge of what is possible and not possible. Thus, the necessitarian argument goes, there is more to laws than universal factual truth—there is some form of natural necessity. It is this feature which permits laws (and not merely accidentally true claims about the universe) to "support" counterfactuals and thereby explain particular occurrences in the world.

The problem of accidental truths arises sharply for empiricists in the Humean tradition who find no warrant from experience for necessity above and beyond the warrant for universal truth. They nevertheless want to distinguish laws from other sorts of true claims and appeal to the systematic connections between scientific statements to judge between the lawful and the lawless truths. Thus, those universal truths which occupy a central place in our systematic explanations of the world (or are included as axioms in the set of claims from which we can derive true statements about the world) are deemed laws. "All spheres of gold found naturally on the earth have a diameter of less than 100 meters" is to be distinguished from "All spheres of uranium found naturally on the earth have a diameter of less than 100 meters." Both are true, and may be true for all time. But the intuition is that while the latter truth is lawful, the former is accidental. It is the perceived failure of empiricist accounts to *explain* regularities that led necessitarians to opt for a richer ontological picture which locates a law's capacity for explanation in relations among universals, inherent propensities or powers, or patterns of facts among realistically interpreted possible worlds.

A range of views can be found in the normativist camp. My concern here is not with the details that differentiate them, but rather with what the general strategy shares. There is general agreement that laws allow us to explain, predict, and successfully intervene in the world. The features which are supposed to allow them to accomplish these functions are:

1. logical contingency (have empirical content),
2. universality (cover all space and time),
3. truth (exceptionless), and
4. natural necessity (not accidental).

How do these criteria get interpreted when scrutinizing knowledge claims to determine their lawful or lawless status? Traditionally, philosophers represent scientific claims that appear in either natural language or mathematical formula in some formal logic. Facts are translated into propositional claims and laws are rendered as universal quantified conditionals (or some properly modalized version of such). $(x)(Px \rightarrow Qx)$ is the familiar reflection of a scientific law in this schema. The functions of laws—i.e., explanation and prediction—are then rendered as deductive (or sometimes inductive) patterns of inference from the suitably formalized law statements to suitably rendered fact statements.

The features of laws as they are traditionally understood and the standard ways of representing them have blinded us to important features of scientific knowledge. While the normativist approach has successfully explicated the strongest versions of knowledge claims that can perform the required functions, "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy" (Shakespeare, *Hamlet*). Part of the problem is a result of the Boolean character of the representational framework of standard logic. Statements are either true or false, and the truth of a statement either follows necessarily from the truth of some other statements (or in virtue of its form) or it does not, i.e., is only contingently true. The insights that scientists acquire about the causal structure of our world may be deformed by being squeezed into Boolean garb. The problems can be seen by considering each of the traditional defining characteristics in turn.

Scientific laws are empirical truths. Their logical contingency will be reflected, in part, by the logical structure of law statement used to represent them. Thus, $(x)(Px \rightarrow Qx)$ is an acceptable form for a law, while $(x)(Px \rightarrow Px)$ is not. How we accurately represent the discoveries of science is open to interpretation. Are F and ma, in Newton's Second Law of Motion, intersubstitutable equivalents? Mach (1883) took this Law to be a definition, and hence to have no empirical content. More recently, philosophers have suggested that we treat certain parts of the set of claims that constitute a research program or paradigm as if they were unfalsifiable, thereby methodologically rendering them analytically true (Kuhn 1962, Lakatos 1970). Indeed, there are well-worn worries about drawing a clear distinction between analytic and synthetic statements. Thus, the feature of contingency characteristic of laws is not uncontroversially displayed by a representation in first order predicate logic.

The second characteristic, universality, is standardly represented by the universal quantifier (x) in $(x)(Px \rightarrow Qx)$. The scope of the quantifier is taken to be all space and all time. Hempel's (1945) solution to the "paradoxes of confirmation" problem that vexed this representation of laws makes clear that the intended scope is this broad. Laws are about our world for all time, and hence all occurrences contribute to the confirmation or disconfirmation of a law. On this interpretation it is taken to be ad hoc to restrict the scope of observations taken as relevant to confirmation. Once the scope of the law is understood as universal in this broadest sense, then it is clear that the truth of the law will permit no exceptions. That is, any point in spacetime that is described as Pa and $\sim$Qa excludes the purported law statement from qualifying as a law.

The necessitarians emphasize that there is more to laws than universal, contingent truth. Natural necessity is also the mark of the lawful. It is this feature which is supposed to distinguish between so-called accidentally true generalizations and lawlike ones, account for the explanatory power of laws, and permit laws to "support" counterfactuals. A problem derives from thinking about natural necessity as isomorphic to logical necessity.

Logical necessity carries the strongest possible warrant from truth of premises to truth of conclusion—the conclusion could not be false. A similar, though not identical, kind of warrant is desired to carry one from occurrence of cause to occurrence of effect in the expression of laws about the natural world—the effect could not be otherwise.

Modeling natural necessity on logical necessity carries with it the presumption that the latter, like the former, is an all or nothing property. Logically, a statement is either necessary or contingent. So nomologically a relation between two events in the world is taken to be either necessary or contingent (i.e., accidental). Because the received view has been wedded to representing epistemological relations (like explanation, prediction, confirmation) and causal relations in first order predicate logic, it has allowed a reification of the features of the representational apparatus to be imposed on the thing represented. The dichotomous character of logical truth/falsity and necessity/contingency is mirrored in the empirical truth/falsity and nomological necessity/contingency relations.

Boolean representations are taken to reflect causal relations characteristic of our world. This leaves no place, except the vast category of non-laws, in which to locate a generalization that describes a strong causal relation between events yet fails to exhibit the strongest conditions of nomological connection. Mendel's law of 50:50 segregation pertains to contingently evolved organisms and, even so, has exceptions among those. Thus, on the traditional account, it fails to satisfy the strong warrant attached to necessary laws. The result of judging biological generalizations by the normativist definition of a law is the conclusion that biology has no laws.

A question may be raised at this point as to what the philosophical enterprise of providing an account of laws of nature aims to accomplish. I believe we should begin with what science has discovered about our world that allows us to explain, predict, and successfully intervene. It is clear that scientists, at least sometimes, use the language of laws to capture

Logically necessary	Logically contingent
	Nomically necessary vs. Nomically contingent

Figure 1. Natural necessity mirrors logical necessity.

the causal patterns detected in the results of observations and experimental set-ups they investigate. In general, what is required for usable knowledge is some claim that one can detach from the particulars of a given observational or experimental situation and export to other contexts (as Feynman clearly states in the quote above). What kinds of information may be used for this purpose? One can attempt to describe the best case, the ideal that, if acquired, would be applicable to all contexts outside of the evidentiary ones. It seems to me that this is the type of law that philosophers have attempted to describe. The normativist law is universal, exceptionless, and necessary, and hence is guaranteed to apply everywhere and for all time. This type of claim will certainly function to predict, explain, and allow us to successfully intervene. Yet when one looks to the actual products of scientific practice, one is hard pressed to find examples that fit that ideal image. Rather, what one does find in scientific papers is a range and variety of models, explanations, and theories that provide us with the tools for intervening in our world. Some scientific laws fail to exhibit the ideal properties of philosophical conceptions of law. The mismatch between the object of philosophical theories of law and the products of scientific practices is implied by Mayr's report of the impact of the debate on the non-existence of laws in biology: "biologists have paid virtually no attention to the argument, implying that this question is of little relevance for the working biologist" (1982, 32).

The working biologist or chemist or social scientist makes do with knowledge claims that fall short of the philosopher's ideal. The appropriate response, I argue, is not to impugn biology, chemistry, and the social sciences for failing to deliver the philosophically valued goods. Rather, this "failure" invites the philosopher to explore just how it is that we manage to explain, predict, and intervene on the basis of these "lesser" variants of lawful relations. How universal, exceptionless, necessarily true generalizations explain, predict, and allow successful intervention is a relatively simple matter compared with how "lesser" variants *actually used in these sciences* manage to perform those same functions. The normativist view of laws and the standard representation of them permits the application of general knowledge of laws to particular events (explanation, prediction, or intervention) by means of instantiation. If $(x)\ (Px \rightarrow Qx)$ is the law, and here we have or will have a case of Pa, then we know to expect that it will be followed without exception by a case of Qa. But what if there are exceptions? What if the "law" applies much of the time but not all of the time? We can use probability to represent expectations in these cases. But often we do not have information about frequencies and sometimes we do have information about the kinds of conditioning factors that make it more or less likely for the general relation to hold in particular cases. Attempts to explicate the way in which causal knowledge of this sort is usable is more profitable than to just relegate those claims to the heap of "accidents." That there is variation among knowledge claims in science is obvious. An understanding of the significance of those variations may well be lost in adopting the ideal image of a law prior to investigating actual scientific claims.

Cartwright (1974, 1983, 1989) has long argued against the normativist conception of laws. In particular she has warned that laws are true only ceteris paribus and describe at best the sanitized, shielded arrangements constructed with great effort in our laboratories. In that sense, they fail to be universally applicable, but apply only when the ideal models which embody their abstract concepts happen to map on to real circumstances. Cartwright's strategy has been to reject the need for laws in science, maintaining the strong, normativist interpretation of laws, and replace them with talk of capacities and nomological machines. (see Cartwright 1999) Thus there is no sting in the charge that biology or the social sciences do not have laws, since we do not need laws to do science. I agree with many of Cartwright's criticisms of laws so construed, and share her concern for explanation of actual events and properties in our world. However, I choose not to concede the normativist interpretation of law. Thus, it is not a mistake on the part of scientists that a variety of knowledge claims in the sciences are designated "laws." I opt instead to argue for a pragmatic reinterpretation of what it is to be a law and thus defend the occurrence of laws in the "non-exact" sciences.

4. Biological Laws and the Continuum of Contingency.

> Today, the word law is used sparingly, if at all in most writings about evolution. Generalizations in modern biology tend to be statistical and probabilistic and often have numerous exceptions. Moreover, biological generalizations tend to apply to geographical or otherwise restricted domains. One can generalize from the study of birds, tropical forests, freshwater plankton, or the central nervous system but most of these generalizations have so limited an application that the use of the world *law*, in the sense of the laws of physics, is questionable. (Mayr 1982, 19)

Beatty (1995, 1997) has recently argued that distinctively biological generalizations, while true, cannot be laws because they are contingent on a particular historical pathway traversed as a result of evolutionary dynamics. Mendel's law of the 50:50 ratio of gamete segregation is true (when it is) only because the genes determining that ratio had been selected for in a particular episode in the evolutionary history of life on this planet. It could have been otherwise, hence it is contingent on that particular evolutionary history and, for Beatty, therefore not a law. Indeed those historical conditions on which the truth of the generalization is contingent (e.g., those determining the selective advantage of the 50:50 segregation gene) may vanish in the future, rendering the generalization no longer capable of truly describing the state of nature. This feature of biological rules Beatty calls 'weak contingency'. In addition, by 'strong contingency' Beatty denotes the situation in which, from the same set of conditions with the same selection pressures operating, variant functionally equivalent outcomes may be generated. Thus, any one of the multiple rules that describe these variant possible outcomes appears not to be necessitated by the prior conditions which gave rise to it: "To say that biological generalizations are evolutionarily contingent is to say that they are not laws of nature—they do not express any natural necessity; they may be true, but nothing in nature necessitates their truth" (Beatty 1995, 52). Thus, the knowledge we have about life on earth is victim to two failures of lawfulness. On the one hand, weak contingency violates the required universality in space and time. Strong contingency points to the exception rich diversity of biological structures and processes that challenge the truth or necessity of any proposed evolutionary generalization.

However, the evolutionary contingency that Beatty attributes to biological generalizations does not separate out biological generalizations from those of the other sciences. All scientific laws or laws of nature are contingent in two senses. First, they are clearly logically contingent. Second, they are all "evolved" in that the relations described in the law depend upon certain other conditions obtaining. That Galileo's law of free fall truly describes relations of bodies in our world requires that the mass of the earth be what it is. If, for example, the core of the earth were lead instead of iron, the quantitative acceleration would be four times what it is (though it would still be an inverse square relation). That the earth is configured the way it is is the result of the origin of the universe, the creation of the stars and planets. Generally stated, there are conditions in our world upon which the truth of laws, like Galileo's law of free fall, depend. They all could have been otherwise. This is the case whether or not those conditions are the result of particular episodes of biological evolution and are subject to further modification, or whether they are conditions that were fixed in the first three minutes of the birth of the universe. Whatever else one believes, scientific laws describe our world, not a logically necessary world.[1] All laws are logically contingent, and yet there is still a difference between Mendel's law of 50:50 segregation and

1. Sober (1997) allows that analytic statements, too, can be laws. Of course there is an issue about what constitutes an analytic statement, that is, whether or not scientific commitments designate certain claims as methodologically analytic. Such matters require more attention that I am able to devote to them here.

Galileo's law of free fall. How can we represent that difference? Beatty is correct to note the difference, but incorrect to identify it with the contingency of the former. That there is a difference between Mendel's laws and Galileo's law should be explained, but it is not the difference between a claim that could not have been otherwise (a "law") and a contingent claim (a "non-law"). What is required to represent the difference between these two laws is a framework in which to locate different degrees of stability of the conditions upon which the relation described is contingent. The conditions upon which the different laws rest may vary with respect to stability in either time or space or both.

The dichotomous opposition between natural contingency and natural necessity in Beatty's discussion can be interpreted as a product of framing natural relations in logical terms. Logical necessity and contingency are indeed dichotomous alternatives. Yet imposing that feature onto the natural relations discovered by science limits what one can express about those relations. The difference between generalizations in physics and those in biology is inadequately captured by the dichotomy between necessity and contingency. They could both have been otherwise. What it would take to make them otherwise is different. They, therefore, have different degrees of stability. The condition that the material forming the core of the earth is iron upon which the strict representation of Galileo's law depends is more stable in space and time than the conditions upon which Mendel's law rests. The actual acceleration of falling bodies, given those conditions, is deterministic, while Mendel's law is probabilistic. Thus, they differ both in stability and in strength.

With this framework in mind, what are the implications for the distinction between accidental truths and laws? That difference, too, will turn out to be a matter of degree and not kind. If we locate different true claims on a continuum, one can better see the distinctions. First of all, it becomes clear that even the so-called accidental generalizations are not all alike (see Figure 2).

Think of the example of the coins in Goodman's pocket all being copper. We can formulate that in the standard model (x) (Px $\rightarrow$ Qx). For all things in the universe, if it is a coin in Goodman's pocket, then it is copper. Recall the counterfactual. If a coin were to be placed in Goodman's pocket, would it be copper? No. A quarter could easily be put in the pocket and falsify the universal generalization. What about the true universal claim that all spheres of gold occurring naturally on the earth have a diameter of less than 100 meters. What conditions are responsible for this truth about our world? What would have to be different for the subjunctive conditional to be false? That there is not sufficient gold in the desired configuration is something quite deep about the history of the universe and the distribution of matter. It is the result of the processes of stellar

Ideal Laws: Contingent, Universal, True

- Law of conservation of mass-energy
- Law of conservation of mass
- 2nd Law of Thermodynamics
- periodic law
- No uranium-235 sphere has diameter greater than 100 meters
- Galileo's law of free fall
- no gold sphere has diameter greater than 100 meters
- Mendel's law of independent assortment
- All the coins in Goodman's pocket are made of copper.

Accidental Generalizations

Figure 2. Continuum of contingency.

fusion and solar system formation. At the origin of the universe in the Big Bang sixteen billion years ago it is believed that only helium and deuterium and ^{7}Li were formed within the first few minutes after that event. All the other elements, including the gold and uranium in our examples have been produced in the subsequent evolution and development of the stars. (Beryllium and boron developed later as well, but by a different process). The spectra of very old stars, which formed over 10 billion years ago, show deficiencies in all elements except hydrogen and helium, and so it is believed other elements have been synthesized since that time (Cox 1989). Thus, there is a sense in which it is impossible, given the history of the universe, that the so-called accidental generalization about gold would be false.

Considering these facts makes the gold example look more like the contrasting uranium so-called law (all spheres of uranium are less than 100 meters in diameter) than the so-called accidental truth about the coins in Goodman's pockets. What conditions would have to be different to undermine the alleged law about uranium spheres? If the ways in which the particles of uranium interact were changed a sphere of 100 meter diameter would be possible. Note that this discussion is not about the conditions stated in the antecedent of the law statement. That is to say, it is not the Px in (x) ($Px \rightarrow Qx$). Rather, I am referring to the conditions which underwrite the truth of the *relation* between P and Q described by the law. In the uranium case, for example, a different configuration, as a sheet rather than a sphere, would permit a mass of uranium equal to one of a sphere of 100 meter diameter to occur. That would not constitute a violation of the law, but merely a $\sim$Pa situation. On the other hand, there may be conditions under which a sphere of uranium would be less likely to reach criticality, and thus it is not inconceivable that there could have been a history of our planet in which it would have been stable. The reasoning here is by analogy.

A similarly entrenched view about the universality of atomic radiation has been shown both theoretically and experimentally to be contingent on certain other conditions. Haroche and Kleppner (1989) have argued that while "spontaneous emission is so fundamental that it is usually regarded as an inherent property of matter" (24), it can be demonstrated experimentally that in certain environments—i.e., by placing an excited atom between mirrors or in a cavity—spontaneous radiation can be greatly suppressed or enhanced. Indeed, they say that spontaneous emission can be "virtually eliminated or else made to display features of reversibility" (24). Thus spontaneous emission from certain excited atomic states thought to be a fundamental, physically necessary feature of matter, turns out to be extremely stable yet nevertheless contingent upon features of the environment in which the atom occurs.[2]

The difference between the examples of Goodman's coins, gold spheres and uranium spheres appears to be in the nature and degree of contingency they display—the conditions which allow the uranium law to truly describe our world are stable and connected with other causal structures in our world. The conditions that allow the gold law to be true are also stable, but less so—if we had "played the tape" of the origin and evolution of the universe again it might have been the case that more of this element would have amalgamated naturally on the earth. Indeed, it may well be that such a configuration of gold may be found elsewhere in the universe.

Having displayed the variation of the nature of contingency of the standard philosophical examples, I now want to show how what scientists have identified as laws are also variable in the same way. At one end of the continuum are those regularities whose conditions are stable over all time and space. At the other end are the so-called accidental generalizations. And in the vast middle is where most scientific generalizations are found. It is my view that to reserve the title of "law" for just one extreme end is to do disservice to science by collapsing all the interesting variations within science into one category, non-laws. Indeed, by doing so we are unable to

2. I wish to thank Ken Smith for suggesting this example.

differentiate them from the least useful of the so-called accidental generalizations, e.g., the coins in Goodman's pocket. By focusing discussion on laws vs. accidental generalizations, natural necessity vs. contingency, one is saddled with a dichotomous conceptual framework that fails to display important differences between the kinds of causal structure found in our world and differences in the corresponding scientific representations of those structures.

At the end closest to the philosophical ideal of exceptionless universality one might place conservation of mass-energy. Lavoisier published his law of conservation of matter in 1789. Leibniz had introduced a law of conservation of energy. In the early part of the twentieth century, with the acceptance of Einstein's theory of relativity, the two laws were combined to express the view that mass and energy are alternative aspects of a single entity. Thus the law of the conservation of mass-energy is now understood to include both the mass of the matter in the system and the mass of the radiant energy in the system. In what sense is this law universal and exceptionless? Prior to the twentieth century, the conservation of matter law would have been thought to be universal and exceptionless. Now we know that it fails to describe relations when energy levels are high enough to allow transformation of matter to energy. Yet, do we now want to say that the conservation of matter is not a law? Scientists use it every day. It allows for reliable expectations in almost all circumstances. Conservation of mass-energy covers more domains. It is now believed to be applicable to all spacetime where mass-energy is present. It is contingent on features of our world that are extremely stable. But even if there were regions where it failed to apply, say near a black hole or because the covariant divergence of the stress-energy tensor was not well-defined in some contexts, it would be no less useful under a wide domain of application. Exceptionlessness is not required for a law to be useful as long as there is some understanding of its domain of applicability

One can place the second law of thermodynamics in a different location on the continuum. What would the world be like for it to be no longer applicable? On the classical formulation it would be a world in which a perpetual motion machine could be built. One could extract work from a closed system of molecules without a corresponding increase in entropy. The statistical interpretation of the mechanism underlying this pattern describes the most probable distribution of molecules interacting with each other and the boundaries of the system. What would the world have to be like for the probable distribution to fail? Notice that even though rather basic features of our world ground this pattern, it is not exceptionless nor universal in the same degree as the conservation of mass-energy. It is possible for entropy to spontaneously decrease. That means, all the matter in our world could be exactly the same, all the laws that apply be exactly the same and still the second law would not accurately describe some part of the universe. It is possible that molecules left to their own devices would congregate in a structured way, but it is unlikely. In fact one can calculate how unlikely it is. Thus though it does not forbid an event occurring that contravenes the second law, the likelihood of it occurring is so small as to be negligible. There is "necessity" here in the sense of expectability, and thus the relations described by the law will obtain and hence one can reliably apply it. However, it is clearly not as strong as mass-energy conservation.

Continuing along, the exact formulation of Galileo's "law" of free fall (including the acceleration due to Earth's gravity) is conditional upon the mass of the earth. If the earth were of a different mass, then it would no longer hold. And that the mass of the earth is what it is is a feature of the evolution of our universe—had the core been lead instead of iron, then acceleration of free falling bodies would be four times as great.

Now to Mendel's law. It states that with respect to each pair of genes of a sexual organism, 50% of the organism's gametes will carry one representative of that pair, and 50% will carry the other representative of the pair. The evolutionary history that makes such a description of our world true is, as Beatty has argued, a function of a particular set of complex circumstances that allowed a genetic mutation for 50:50 segregation to appear in an environment where it was more fit than other variants, in a context where other features of the organisms were not traded off via other selective pressures, where chance and mutation and migration did not override the selective advantage, and so on. If any one of those conditions had been otherwise, a different genetic evolution might have occurred and the law would find no application in predicting, explaining, or intervening in our world. That is, given that the circumstances did occur, Mendel's law operates to perform the functions we require of laws.

Is conservation of matter not a law if it fails to apply in nuclear reactions? No. That most of the universe's physical systems are structured in a way that accords with the relation described lets us use the "law" to explain and predict successfully. Does Mendel's law of 50:50 gamete segregation fail to be a law because it does not apply to the entire temporal period prior to the evolution of sexual reproduction nor to cases where a mutation for meiotic drive changes the relative fitness ascriptions? Where the requisite conditions hold, Mendel's law also allows us to explain and predict successfully.

The difference, then, between the two is not that one functions as a law and the other does not, or that one is necessary and the other is contingent. Rather the difference is in the stability of the conditions upon which the relations are contingent. Consequently there is a difference in the kind of information required in order to *use* the different claims. It would be great if we could always detach the relation discovered from its evidential context, and be assured it will apply to all regions of spacetime. But virtually no scientific law is so unrestricted. Whether it is in space or in time, there are regions where the relations described will hold and regions where it will not hold. The conditions that describe those regions are the conditions upon which the truth of the relations is contingent. In order to apply less than ideally universal laws, one must carry the evidence from the discovery and confirmation contexts along to the new situations. As the conditions required become less stable, more information is required for application. Thus the difference between the laws of physics, the laws of biology, and the so-called accidental generalizations is better rendered as degrees of stability of conditions upon which the relations described depend, and the practical upshot is a corresponding difference in the way in which evidence for their acceptance must be treated in their further application.

How can one represent these degrees of stability and strength? Philosophers have certainly developed alternatives to the first order predicate calculus to represent regularities (Suppes 1984, Skyrms 1980, Woodward 1997, Spirtes et al. 1993). The probability calculus is the most obvious. More recent developments include causal graphs and computer models. These alternative representations do not suffer some of the limitations of standard formal logical systems. For some of the causal structures that scientists might refer to as "laws," these are better representations. For example, they are better representations of "laws" of thermodynamics and of economics. For some causal structures, the additional representational machinery appears not to be necessary, e.g., the law of mass-energy conservation. What's the lesson? The lesson is that one representation really cannot capture the structural features of all the kinds of casual structures found in nature. But this result is only the first step in accepting that a characterization of "laws" is going to have to be a complex one.

The next step is the recognition that no structural representation of the degree of abstraction provided by the first order predicate calculus, the probability calculus, or causal graphs is sufficient to completely characterize a causal structure for the purposes of explanation and prediction. Why? Because they do not include the conditions of applicability of the laws when they are used for these purposes. Consider the ideal gas law: $PV = nRT$. As every elementary text says, this law applies when "the energy of interaction between the molecules is almost negligible compared to their kinetic energy" (Reif 1987, 176). In an actual laboratory measurement setting, even that condition of applicability has to be translated into a particular situation in terms of the kind of gas, the temperature, and the pressure in question. There is also the obvious fact that the law does not apply as the number of molecules of the gas in question become small. In short, there are a very large number of characteristics of this "law" qua claim about the world that are not captured in an algebraic equation (or the first order predicate universal form of that equation). These characteristics are relevant to the applicability of this claim for explanation and prediction. These characteristics, I will claim, are constituents of a complex characteristic space that is the appropriate analytical framework from which to understand any particular scientific claim and from which to understand the relations between the various kinds of claims that scientists make. This complex space includes a number of characteristics that determine the applicability of a law. Many of these characteristics are multi-valued or even continuous valued. Thus it has both more degrees of freedom and more complex descriptive parameters than the traditional accounts.

Initial approaches to describing some of the dimensions of the characteristic space for generalizations have already been taken. Skyrms and Woodward have recognized differences in degree of lawfulness in the claims of science. Both describe the lawful character of generalizations by appeal to the resiliency of the relations described by the claim. Within their intended domains described relations will exhibit some degree of resiliency—the probability of the consequent condition on assumption of the antecedent condition will be more or less stable. For universal generalizations, the probability is one that within the specified domain no counterexample will be found. If it is maximally resilient, then it will be exceptionless. But it may be less resilient than that and still afford us reliable expectations of what will likely occur. Hence Skyrms allows for the representation of less than ideal lawful relations. The variation he permits is in the strength of the relation (and, hence, corresponding expectation) between the factors in a specified domain. Woodward develops his concept of resiliency as a condition for explanatory power by appeal to the kinds of interventions one could make in a set up and still have the generalization correctly describe the results. The more resilient, the fewer interventions will issue in a failure of the relation to hold. Thus Woodward explores the domains of applicability that permit the lawful relation to hold. With these refinements, Skyrms and Woodward want to retain a law/non-law dichotomy. Skyrms says,

> [S]o I would say that it [no gold sphere has diameter more than 100 m.] has more nomic force than the generalization about coins in Goodman's pocket on V. E. day, but less than anything we would regard as a genuine law. . . . the more nomic force, the more central the law is to our conceptual scheme, that we are less willing to give up a law than an accidental generalization, that giving up a law is more disruptive to our conceptual scheme than giving up an accidental generalization, and the more nomic force the greater the disruption. (1980, 60)

My view differs in at least positing that what makes it more or less difficult to "give up" a claim in any given circumstance is the nature of the conditions under which the generalization is applicable. Skyrms's and Woodward's analyses describe some dimensions of the multidimensional space of characteristics that more adequately represent laws and their applicability. Filling out the rest of the details is to give a pragmatic view of laws and their operation in science.

5. The Pragmatic Strategy. Taking a pragmatic approach to scientific laws replaces a definitional norm with an account of the *use* of scientific laws. How do they function to allow us to make predictions, explanations, and successful interventions? The result is a framework for representing the multiple types of generalization found in the sciences. In contrast to the dichotomous space defined by the normative approach this view requires a multi-dimensional frame in which to view the varied conditions of applicability of scientific generalizations.

Scientists search for knowledge of the causal structures in our world. When we know what sorts of properties or events are causally relevant to the production of other properties or events, then we can use that knowledge in pursuing both scientific and practical ends. Again, it would be ideal if we could always detach the generalizations gleaned from specific investigations from their supporting evidence, carry these laws to all regions of spacetime, and be ensured of their applicability. Such generalizations would be universal and exceptionless. But some causal structures—in particular those studied by biology and the social sciences—are neither global nor exceptionless. Thus the generalizations describing them cannot be completely detached from their supporting evidence. Nevertheless, we can and do use these more limited tools to do the jobs we set out to do. To know when to rely on a generalization that does not apply to all space and time we need to know when it will apply, and this can be decided only from knowing under what specific conditions it has applied before and the caveats its mode and manner of representation warrant for explanatory and predictive applications.

In my 1997 paper I distinguished between two general types of parameters which structure the applications of scientific regularity claims—ontological and representational. Scientific knowledge consists of claims about the causal structure of the world and at the same time are represented in some form, be it linguistic, mathematical, or visual. The complexity that is reflected in the diversity and plurality of claims in the sciences reflect both ontological differences among the causal structures in the domains studied and in other features of the representational medium.

The ontological parameters include what I have been calling the continuum of stability of the conditions upon which the causal relation depends. As we saw, in the case of Mendel's law of 50:50 segregation, that relation will hold just so long as the genetic and environmental conditions persist which render 50:50 segregation adaptive. Much can happen to perturb those conditions, including the introduction of a gene that induces meiotic drive (while at the same time not being coupled with other maladaptive effects, like sterility as in the case of the T-allele in the house mouse). With the second law of thermodynamics, one ontological requirement is that our subject be a system with a large number of molecules.

The second ontological parameter is what I have called a continuum of strength and it refers to the relation described by the arrow in $(x)(Px \rightarrow Qx)$. It refers to the difference in strength between a deterministic law and a probabilistic one. It seems clear than one of the ways in which biological laws have been understood to fail to meet the ideal standard, is by being non-deterministic. Mayr clearly means this when he says, "Generalizatons in biology are almost invariably of a probabilistic nature . . . only one universal law in biology "All biological laws have exceptions" (Mayr 1983, 38). In addition to the ontological parameters the other parameters that are relevant to the applicability of generalizations include:

- **degree of abstraction.** Some patterns will be visible only when certain details are ignored.
- **simplicity.** We use generalizations ranging from rules of thumb like Ptolemaic astronomical "laws" to navigate, to ideal gas laws that yield approximations within engineering tolerances.
- **cognitive manageability.** Prior to the development of high-speed computation, mathematical equations were restricted to solvable linear formulations. This dimension may include both computational tractability and human cognitive accessibility.

I do not claim this to be an exhaustive list. In fact, I believe better characterizations of "laws" will require both filling out the details about the characteristics listed here as well as extending this list. I have already described in some detail the characteristic of stability and the characteristic of strength. I will now turn to a discussion of abstraction.

With respect to degree of abstraction (see Cartwright 1989), one sees that different levels are required for different tasks. For example, Darwin's insight into the causal patterns responsible for adaptedness was a reflection on the similarity between the varieties of cowslip and English game pigeons. Nearly all material properties of the two populations are different, except that they are made of organic molecules, and have DNA and mass. What was seen as similar was the fitness of the surviving members of the populations to their respective environments. In order to explain the adaptedness of species, a feature that had seemed indisputably the result of the design of a creator, Darwin detected a pattern in the various populations that had a single, mechanical explanation. Natural selection operating on variations would cause those with any slight advantage to be more likely to reproduce, and, if heritable, the advantageous feature would be more likely to persist through subsequent generations. This is the case whether the advantage be a taller stalk, thicker beak, or darker pigmentation (see Mitchell 1993). The schematic character of this "law" has been emphasized by Brandon (1978) and others, recognizing the great deal of "local information" required to apply the knowledge of evolutionary causal structures to concrete cases.

In chemistry, there are a variety of configurations of molecules that we identify as water or as hemoglobin.[3] Representing these differences is useful for different purposes. We can treat water abstractly to refer to all isotopes of H_2O as well as configurations that replace the hydrogen with deuterium which has one neutron or tritium which has two. Hydrogen has no neutrons. They all have one proton and one electron. So we could have T_2O, DOT, HOT, etc. There are two isotopes of Oxygen O-17 and O-18. In all there are 18 possibilities. When can we abstract away from these variations and treat a situation as one containing water and describe usable causal regularities? Replacing hydrogen in a molecule with deuterium can slow down the rate of the reaction. Deuterium is almost twice as heavy as hydrogen so it moves slower. Deuterium has different spectroscopic properties than hydrogen. Their resonance properties vary. This difference is useful to represent in proton nuclear magnetic resonance contexts. For example, such procedures are often performed in deuterated solvents, so that the only hydrogen in a sample will be from the molecule being analyzed. Thus replacing $CHCl_3$ with $CDCl_3$ removes hydrogen from the surrounding medium to allow detection of hydrogen only in the test sample. But for studying tidal properties of the ocean, for example, representing these differences would be confusing and unnecessary.

The case for hemoglobin is even more complex. Hemoglobin contains 2,954 carbons, 4,516 hydrogens, 780 nitrogens, 806 oxygens, 12 sulfurs, and 4 irons. There are 3 natural isotopes of carbon, 2 of nitrogen, 2 of oxygen, 4 of sulfur, and 4 of iron. The number of possibilities for different isotopes is so large that there are almost certainly no two identical hemoglobin molecules in an individual's body. This is the case even when we consider that one drop of blood contains 10^{17} molecules.

If we make the simplifying assumption that all isotopes are equally probable, the number of different hemoglobin molecules is a number with 4132 decimal places. That is, the order of magnitude is 1×10^{4132}. This means there are about 5×10^{20} different kinds of molecules in an individual's body (assuming no two are the same). To collect all the possible

3. I owe these examples to Michael Weisberg.

hemoglobin molecules, we would need at least 2×10^{4111} people. Of course, there are only about 5×10^{9} people in the world.

When would we want to represent the molecules in sufficient detail to capture these differences? When is the level of abstraction that refers to all isotopes as hemoglobin *simpliciter* adequate? These questions can only be answered with reference to a particular context and scientific objective. For most chemical reactions these differences are negligible since the chemical behavior of a molecule is a function of its shape and electronic configuration. The variations between isotopes in electronic structure are negligible. The level of abstraction we need to represent a situation is determinable only by the problem we wish to solve—the use to which the knowledge is to be put.

Different tools will be better at solving different problems. What we should expect to see in the sciences is a diversity of models, theories and levels of abstraction. And, indeed, Feynman describes the heuristic benefit of multiple representations of empirically equivalent theories.

> psychologically we must keep all the theories in our heads, and every theoretical physicist who is any good knows six or seven different theoretical representations for exactly the same physics. He knows that they are all equivalent, and that nobody is ever going to be able to decide which one is right at that level, but he keeps them all in his head, hoping that they will given him different ideas for guessing. (1995, 168)

That different representations may be better suited to different tasks is obvious. If I want to navigate in the city of Washington, D.C., to find the Capitol building, it will be equally unhelpful to have either a one:one full-scale representation of the city and its buildings, or to represent Washington as a single point on a map of the U.S. (see Eco 1994).

The details on the rest of the list of characteristics in the complex space of the pragmatic account of laws will have to be left for future work. But having the general account and some specifics about the characteristics of stability, strength, and degree of abstraction addresses the original conundrum: How can there be no "laws" in biology when biologists think they use laws all the time to explain and predict?

The failure of knowledge claims in biology or other sciences to live up to the universal, exceptionless character of the ideal case does not preclude their functioning as "laws"—generalizations that ground and inform expectations in a variety of contexts. When we are entitled to have a particular expectation (the scope of domains to which we can export an empirically discovered relation) and the degree of strength of that expectation (in terms of probability or complexity) are dimensions that can be used to compare generalizations within physics or biology, as well as between them. In the multi-dimensional space defined by the multiple aims of scientific practice including the ontological parameters as well as degree of abstraction, simplicity, and cognitive manageability, it may well turn out that all or most of the generalizations of physics occupy a region distinct from the region occupied by generalizations of biology (see Figure 3). The conditions upon which physical laws are contingent may be more stable through space and time than the contingent relations described in biological laws. The conservation of mass/energy law is more stable than Mendel's law of segregation. The strength of the determination can also vary from low probability relations to full-fledged determinism, from unique to multiple outcomes. Indeed the causal contribution of particular features may vary in their sensitivity to environmental conditions, their resilience in Skyrms's and Woodwards's senses. In terms of abstraction, Mendel's law may be considered more abstract than the law governing the possible configurations of Uranium. While I have only sketched the parameters by which knowledge claims may be compared, it is clear that such a conceptual framework has the resources to display the multiple relationships that exist among and between generalizations in the sciences. The world is complex and so must be our scientific representations of it. So too, for the world of scientific knowledge.

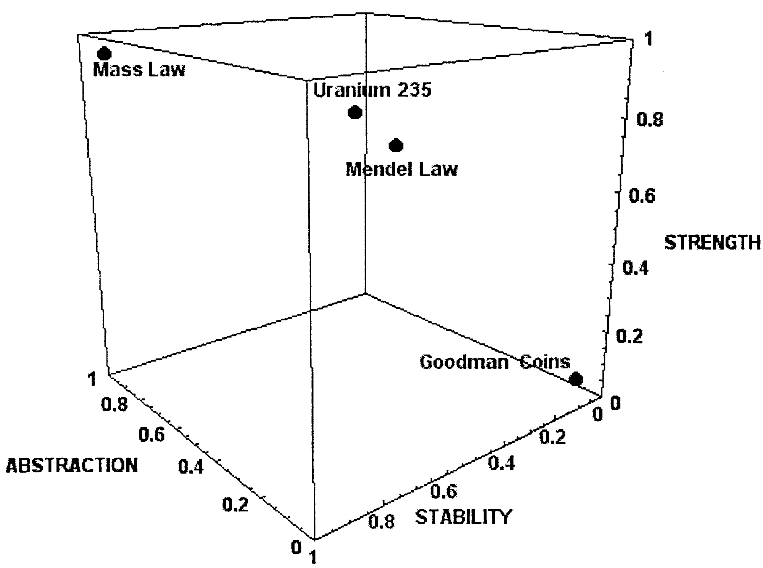

Figure 3. Multi-dimensional conceptual space for scientific laws.

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