## Chapter 4

# Structures of Scientific Theories[1]

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## Introduction

A central aim of science is to develop theories that exhibit patterns in a domain of phenomena.[2] Scientists use theories to control, describe, design, explain, explore, organize, and predict the items in that domain. Mastering a field of science requires understanding its theories, and many contributions to science are evaluated by their implications for constructing, testing, and revising theories. Understanding scientific theories is prerequisite for understanding science.

The two dominant philosophical analyses of theories have sought an abstract formal structure common to all scientific theories. While these analyses have advanced our understanding of some formal aspects of theories and their uses, they have neglected or obscured those aspects dependent upon *nonformal* patterns in theories. Progress can be made in understanding scientific theories by attending to their diverse nonformal patterns and by identifying the axes along which such patterns might differ from one another. After critically reviewing the two dominant approaches (pp. 55–64), I use *mechanistic theories* to illustrate the importance of nonformal patterns for understanding scientific theories and their uses (p. 67).

## The Once Received View (ORV)

Central to logical positivist philosophy of science is an analysis of theories as empirically interpreted deductive axiomatic systems.[3] This formal approach, the ORV,[4] emphasizes inferential patterns in theories. The primary virtue of the ORV (and some of its vice) lies in its association and fit with argument-centered analyses of, for example, explanation, prediction, reduction, and testing. The main commitments of the ORV are as follows.

### *Logical and extralogical vocabulary*

According to the ORV, theories are linguistic structures composed of a logical and an extralogical vocabulary. The logical vocabulary contains the operators of first-order predicate calculus with quantifiers, variously supplemented with relations of identity, modality, and probability.[5] The extralogical vocabulary ($V$) contains the predicates that constitute the theory's descriptive terms. Theories systematize phenomena by exhibiting deductive and inductive inferential relations among their descriptive terms; this systematization provides a "logical skeleton" for the theory and "implicitly defines" the predicates in $V$ (Nagel, 1961, p. 90).

### *Correspondence rules and the theory/observation distinction*

The predicates of $V$, on the ORV, can be sorted into an observational vocabulary ($V_O$) and a theoretical vocabulary ($V_T$). Predicates in $V_O$ are defined directly in terms of the observable entities and attributes to which they refer. The predicates in $V_T$ refer to entities and attributes that cannot directly be observed; these predicates are defined indirectly via *correspondence rules* tethering them to predicates in $V_O$.

Correspondence rules give theories their empirical content and their explanatory and predictive power. Correspondence rules have been characterized as explicit definitions (including operational definitions), as reduction sentences (partially or conditionally defining the term within the context of a given experimental arrangement), or in terms of a more holistic requirement that the theory form an interpretive system with no part failing to make a difference to the observable consequences of the theory (Hempel, 1965, chs 4 and 8).

### *Laws of nature*

On the ORV, the explanatory power of theories springs ultimately from the laws that are their axioms. Explaining an event or regularity (the explanandum), on the "covering law" account, is a matter of inductively and/or deductively systematizing (fitting) the explanandum into the axiomatic structure of the theory and thereby demonstrating that the explanandum was to be expected given the laws of nature and the relevant conditions.

Within the ORV, law statements (descriptions of laws) are canonically represented as universally quantified material conditionals (e.g., "For all $x$, if $x$ is $F$ then $x$ is $G$"). Minimally, law statements are

(i) logically contingent
(ii) true (without exception)
(iii) universal generalizations, that are
(iv) unlimited in scope.

Requirement (iv) is generally understood to preclude the law's restriction to particular times and places. Many recommend the additional requirement that the regularity described by the law statement (v) hold by physical necessity. This requirement might be used to distinguish statements of law from merely accidental generalizations (Hempel, 1966, ch. 5), or to pick out those generalizations that support counterfactuals from those that do not (Goodman, 1983).

## *Theory construction, theory change, and derivational reduction*

The ORV is commonly associated with a generalization/abstraction account of theory construction, a successional account of theory change, and a derivational account of intertheoretic reduction. The strictures of the ORV restrict its flexibility for analyzing theory construction and theory change.

The *generalization/abstraction account* depicts theory construction as a "layer cake" inference *first* from particular observations (via inductive generalization) to empirical generalizations constructed from $V_O$, and *then* from these empirical generalizations (via e.g., hypothetico-deductive inference) to laws of nature (constructed from $V_T$). This account is not mandated by the ORV, but its logical framing of the theory construction process (with its dichotomies of type and token, general and particular, observable and theoretical) naturally suggests such a picture; see, for example, Nagel (1961, ch. 5).

The ORV's analysis of meaning enforces a *successional account* of theory change. First, the ORV individuates theories too finely to illuminate the gradual and extended process of theory building. The weakening of correspondence rules to an "interpretive systems" requirement in effect ties the meaning of any term in $V$ to its inferential relationships to all of the others. Even relatively insignificant changes, such as the development of a new experimental technique, produce an entirely different theory (Suppe, 1977). Understanding gradual theory construction requires a diachronic notion of theory that persists through such changes (Schaffner, 1993a, chs 3 and 9).

The ORV analyzes successional theory change as *intertheoretic reduction or replacement*. On the most sophisticated account – Schaffner's generalized reduction/replacement (GRR) model (1993a, ch. 9) – reduction is the deductive subsumption of one (corrected) theory by another (restricted) theory. The reduced theory often has to be corrected because it is literally false, and the reducing theory often has to be restricted because the reduced theory is a special case of the reducing theory. As more revision and restriction are required, it becomes more appropriate to describe the successor theory as replacing, rather than reducing, its predecessor.

Some reductions are interlevel; theories about one intuitive ontic level are deductively subsumed by theories at another intuitive ontic level (as in the putative reduction of the ideal gas laws to statistical mechanics). This derivational view of interlevel relations tends to enforce a stratigraphic picture of science and of the world – a picture in which ontological levels map onto levels of theory which in turn map onto fields of science (Oppenheim and Putnam, 1968). On this caricature, theories at each level develop in relative isolation until it is possible to derive the higher level theory from the lower. Schaffner's inclusion of correction and revision in the GRR model accommodates the fact that theories at different levels may co-evolve under mutual correction and revision (Churchland, 1986; Bechtel, 1988).

## Criticisms of the ORV

Virtually every aspect of the ORV has been attacked and rejected, but there is no consensus as to where it went wrong. There are as many different diagnoses as there are perspectives on science and its philosophy.[6] Here, I focus on the limitations of the ORV for describing theories "in the wild" (i.e., as they are constructed, conveyed, learned, remembered, presented, taught and tested by scientists). The charges are that

- the ORV misdescribes theory structure(s) in the wild (p. 58)
- the ORV distorts theory dynamics in the wild (p. 60), and that
- the ORV's emphasis on laws of nature makes it inapplicable to many accepted theories (p. 62).

### *Theory structure in the wild*

The ORV is not typically defended as an accurate description of theories in the wild; rather, it is a regimented reconstruction of their shared inferential structure. A descriptive gulf between the ORV and theories in the wild can nonetheless suggest

(i) that there are important structures of scientific theories that are neglected, de-emphasized, or at best awkwardly accommodated by the ORV, and
(ii) that there are significant aspects of the ORV that are peripheral to the uses of theories in the wild.

Attention to inferential structure pays dividends for regimenting arguments, but inferential patterns do not exhaust the useful patterns in scientific theories.

*Multiple, partial, and incomplete theory formulations are neglected or homogenized*
Theories in the wild are sometimes written in a natural language; they are also charted, graphed, diagrammed, expressed in equations, explicated by exemplars, and (increasingly) animated in the streaming images of web pages. Only rarely are

theories represented in first-order predicate calculus. Even the theories most amenable to tidy treatment on the ORV can be given different equivalent logical formulations and can be scripted with different formalisms, and these differences often significantly influence how the theories are used and how they represent the patterns in a domain. Regimenting theories into the ORV structure obscures the diverse representational tactics used by scientists when they deploy, express, and teach their theories; see, for example, Nersessian (1992).

Representations of theories in the wild are also often *partial or incomplete.* Trumpler's (1997) historical study of the development and refinement of different visual representations of the $Na^{2+}$ channel is an excellent example. The theory, in this case, is partially represented by a host of representations (e.g., images of primary, secondary, and tertiary protein structure, circuit diagrams, current-to-voltage graphs, cartoons of possible mechanisms like that shown in Figure 4.1), none which represents the theory of how the $Na^{+}$ channel works in its entirety. Learning this theory involves internalizing these representations and mastering the reticulate connections among them. Theories in the wild are also frequently incomplete as they are cobbled together over time. Such incompleteness blocks derivational arguments, but is treated as an innocuous fact of life in science as practiced.

*Nomological patterns emphasized over causal/mechanical patterns* Many criticisms of the "covering law" account of explanation turn on the importance of *causal/mechanical* rather than merely *nomological* patterns in our examples of intuitively good explanations. There are many now familiar examples – propagated in part by W. Salmon (1984; 1989): the elevation of the sun and the height of the flagpole explain the length of the pole's shadow and not vice versa; falling barometric pressure, and not the falling mercury in the barometer, explains the ensuing storm; and the current positions of the planets can be explained on the basis of their positions yesterday but not on the basis of their future wandering. Examples of this sort (and similar counter-examples to inductive explanations) can be used to argue for the explanatory importance of explicitly causal/mechanical patterns rather than merely inferential or nomological patterns; see Salmon (1989) but also see Kitcher (1989). Such criticisms apply equally to the descriptive adequacy of the ORV for accommodating and highlighting causal/mechanical patterns in theories; see page 67.

*Mathematical structures are awkwardly accommodated* Finally, the restriction of the ORV to the first-order predicate calculus awkwardly accommodates the mathematics, statistics, and probabilities required for expressing the theories of, for example, quantum mechanics, relativity, and population genetics. As proponents of a model-based view of theories have emphasized (p. 64), set-theoretic (Suppes, 1967) and state-space approaches (Suppe, 1989) to representing theories naturally accommodate these mathematical relations and, in many cases, are, in fact,

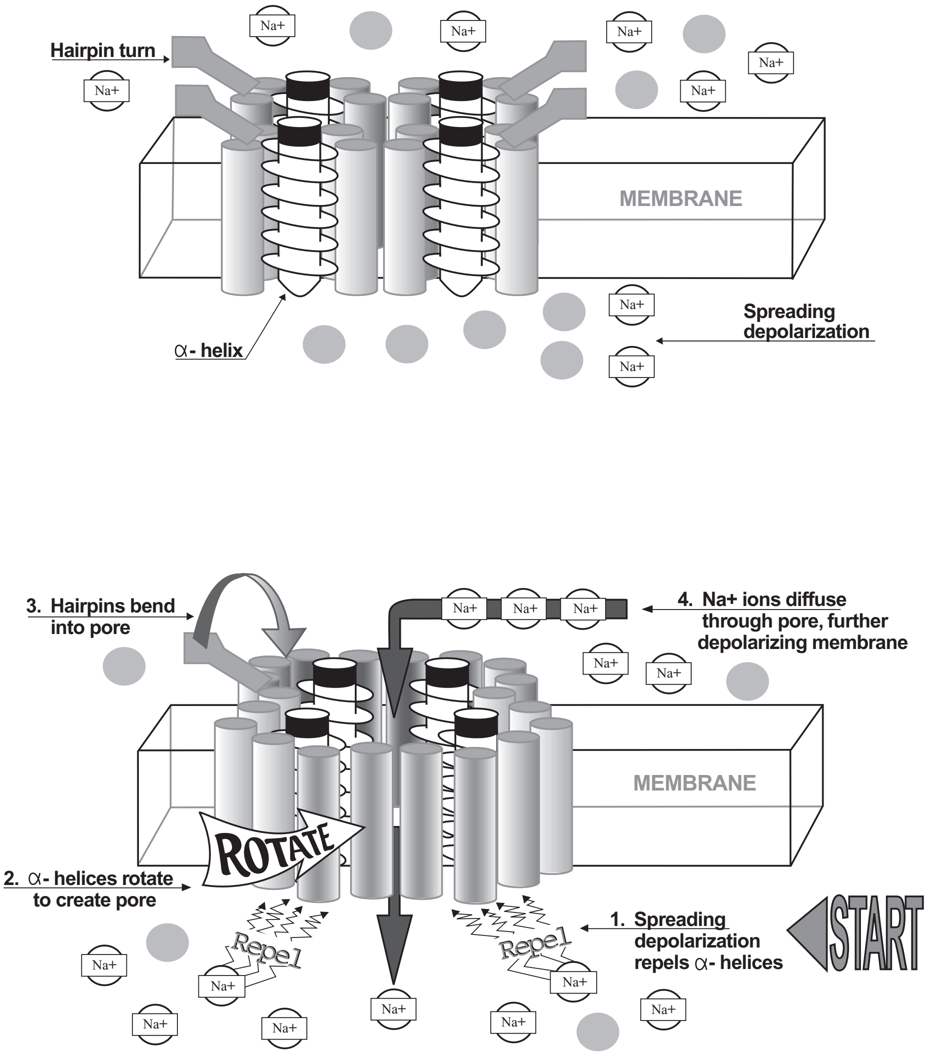

*Figure 4.1*

the representational conventions favored by the scientists (McKinsey and Suppes, 1953a, 1953b; Suppe, 1989).

## *Theory dynamics in the wild*

A second major criticism of the ORV's descriptive adequacy is that it neglects or distorts the *dynamics* of scientific theories – the protracted process of generating, evaluating, revising, and replacing theories over time. For example, Darden (1991, ch. 2) argues that discovery has been neglected by traditional ORV-based approaches; Lloyd (1988) develops her alternative account of scientific theories to highlight aspects of theory testing that are neglected on the ORV; and Schaffner (1993a) emphasizes the importance of developing a diachronic account of theories. Close attention to science and its history have revealed aspects of theory dynamics that are neglected, or awkwardly accommodated within the ORV's strictures.

The generalization/abstraction account of theory building treats theory building as the joint application of inductive generalization and hypothetico-deduction. These strategies are incomplete, and leave unanswered questions about which inductive generalizations to draw (Goodman, 1983) and about how scientists generate the hypotheses from which to deduce predictions.

Successional accounts of theory change neglect or distort the gradual and piecemeal character of theory building. In the wild, grand clashes between rival hypotheses are infrequent and isolated compared to the more common process of articulating, refining, and elaborating a single theory over time. However, making sense of this gradual and piecemeal process of cobbling a theory together requires a diachronic notion of theories with criteria of individuation that accommodate such gradual changes. Arguments for the theory-ladenness of observation statements gloss successional theory change as a paradoxical choice among incommensurable theories (Kuhn, 1962; Feyerabend, 1965), obfuscating the reasoning involved in theory change over time. Furthermore, the ORV obscures the targeted nature of theory construction because the theory's ramified meaning structure makes it difficult to target praise or blame at parts of the theory. For these reasons, the ORV diverts attention from gradual and piecemeal construction, evaluation, and revision of theories over time; see Darden (1991, ch. 2) and compare with Wimsatt (1976).

Finally, the ORV's derivational account of reduction has been the subject of a variety of attacks discussed in Chapter 5 of this volume. One criticism worth emphasizing here is that derivational reductions are largely peripheral to many cases of reduction and theory succession in the wild (Schaffner, 1974; 1993a) and are accomplished, if ever, long after the interesting science is completed (P. S. Churchland, 1986, ch. 9). The derivational account of intertheoretic reduction is also unforgiving of gaps in the deductive argument, although, in the wild (there are many good examples in molecular and evolutionary biology, neuroscience, and medicine), both the predecessor and the successor theory are partial and incomplete to the point that derivation is out of the question. Additionally, the relationship between levels, scientific fields and theories has proved significantly more complicated than the Oppenheim–Putnam stratigraphy would suggest; both theories and fields in the biological sciences, for example, are characteristically multilevel.

The rigid strictures of the ORV leave it ill-suited for dealing with gradual and piecemeal theory change and also for highlighting the nonformal patterns that scientists use to construct, evaluate, and revise their theories.

### *Theories and laws*

A third objection to the ORV is that there are legitimate theories in the wild (in e.g., molecular and evolutionary biology, neuroscience, and medicine) that lack ORV-style laws. Many have denied the importance of laws in physics as well (Cartwright, 1983; Giere, 1999). It would be dogmatic and unmotivated to insist that these scientific products are not theories. It is more plausible either

(a) to insist that these theories do contain ORV-style laws, or
(b) to give up the law requirement altogether.

Most have chosen some variant of (b). Opponents of (a) argue that the central generalizations in such theories are nonuniversal or restricted in scope (see next subsection), that they are physically contingent (p. 62), or that law statements in the wild are typically either false or vacuous (p. 63). Most advocates of (b) have chosen either to replace (or redefine) the notion of a law with something less stringent (p. 63) or to sidestep the issue entirely (p. 64).

*Laws, universality, and scope* ORV-style laws are universal, unrestricted and exceptionless. Rosenberg (1985), Schaffner (1993a), and Smart (1963) have each suggested that (most) biological theories fail to satisfy these requirements. Theories in these domains hold only on earth (they are, at best, "terrestrially universal"), they often hold only for particular species, and they have exceptions even within species. Even the best candidates for universal biological laws, such as the theories of the genetic code and protein synthesis, are unlikely to hold for exotic life forms (e.g., in distant solar systems), and are known to have earthbound exceptions. Viruses use RNA as their genetic material, and proteins can be synthesized without a DNA template (Darden, 1996, p. 410); see also Beatty (1981, 1995). Thus biological laws are often restricted to particular species, strains, and individuals. This feature is not unique to the laws of biology; see Lange (1995) and Giere (1988, ch. 3; 1999, ch. 6).[7]

*Laws and necessity* A second difficulty for ORV-style laws in biological theories is that many of the generalizations in such theories hold only by the grace of evolution by natural selection, and so are evolutionarily contingent (Beatty, 1995). Such generalizations might not have come to hold and may, some day, no longer hold. But laws are supposed to express what must necessarily be the case rather than what is accidentally (or contingently) the case. Beatty thus raises a rather more specific form of quite general worries about the kind of necessity by virtue of which statements of law can sort accidental generalizations from nonaccidental laws or generalizations that support counterfactuals from those that do not.

One important challenge, if one is to maintain these distinctions, to do so without running afoul of what Earman (1986) calls an "empiricist loyalty test" and Lewis (1986) calls the doctrine of "Humean Supervenience" (HS). HS is the requirement there be no difference in the laws of nature without there being a difference in past, present, or future occurrent facts (i.e., particulars, their manifest properties, and their spatiotemporal relations). As Roberts (1999) argues, denying HS

(i) amounts to a commitment that knowledge of the laws of nature is in principle forever beyond our grasp (the "epistemological problem") and
(ii) leaves one unable to specify which set of true propositions is the extension of the term "law of nature" (the "semantic problem").

The importance and tenability of HS have been challenged by Carroll (1994). Yet reconciling nomological necessity with HS remains a major challenge for the philosophy of science. Some are driven by these empiricist intuitions in HS into denying that there is any form of physical or natural necessity; this cement or glue is to be found only in models and not in the phenomena in their domains. Still others have sought this natural necessity in causal relations among objects, processes, or events. These suggestions are well beyond the scope of the present discussion.

*Laws in the wild are typically inaccurate or vacuous* A third challenge for the ORV's emphasis on laws is that the best examples of laws hold only under a range of conditions that typically do not obtain, that cannot obtain or that cannot exhaustively be described (and so are glossed by so-called "*ceteris paribus*" clauses). Many laws hold only under extreme conditions (e.g., in the absence of air resistance, or assuming all other gravitational effects are negligible), and many specify what will happen under idealized conditions (e.g., assuming frictionless planes and point masses). In an effort to spell out the law's *ceteris paribus* conditions, one risks turning laws into meaningless truisms, i.e., the theory holds unless it does not hold (Hempel, 1965, pp. 166–7). On the other hand, unless all possibly confounding conditions are included in the law statement, the law is inaccurate. Criticisms of this sort have been most rigorously pursued by Cartwright (1983) and Giere (1999); for counter-arguments, see Earman and Roberts (1999).

*Weakening the law requirement* One response to criticisms of ORV-style laws is to replace them with a weaker alternative. However, there is no foreseeable consensus as to what that alternative should be. Schaffner (1993a) distinguishes universal generalizations$_1$ and universal generalizations$_2$, the former applying to "all (terrestrial) organisms" (p. 121), and the latter "referring to the property illustrated by the phrase 'same cause (or same initial conditions and mechanisms), same effect'" (p. 121). Generalizations may have a restricted scope or known exceptions, but this does not detract from the fact that these generalization have the kind of necessity associated with the support for counterfactuals. Also, focusing on the importance of counterfactual support, Woodward (1997) has suggested that the required physical necessity can be supplied by "invariant" generalizations, those that hold under a range of interventions and so can be used to control or manipulate (and hence understand) some effect under conditions within that range (which may be rather limited). Still more pluralistically, Mitchell (2000) has suggested that ORV-style emphasis on universality, nonaccidentality, and unrestrictedness produces, "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" (p. 243). In a similar spirit, Lange (1995) argues that laws of nature, as identified in scientific practice, need be neither exceptionless nor unrestricted to particular times and places. Instead, he suggests that statements of laws be identified by their functions in the practice of science and be characterized as warrants for reliable inferences (in the service of relevant purposes).

It is not necessary to abandon the ORV to accommodate theories without ORV-style laws of nature; one need only amend it by removing the law requirement or replacing it with something else. Some characterize laws as the axioms of the best system for describing the world, thus effectively removing the need to provide a conceptual analysis of law talk in terms of a checklist of properties they all share (Lewis, 1986). Others have sought to divorce the discussion of laws from discussion of theory structure by making claims about scope, necessity and universality extrinsic to the theory (p. 64).

### *Conclusion*

Although the ORV neglects or distorts a wide range of interesting questions about science, an understanding of the logical patterns in scientific argument is indispensable for any account of the epistemology of science, and so the ORV is really the once *and future* received view, at least for some central questions in philosophy of science. Yet, the ORV is awkward at best in its treatment of theory building, laws, and the nonformal patterns exhibited by theories in the wild.

## The "Model Model" of Scientific Theories

Some critics of the ORV have found its failings so systematic as to warrant an alternative formal approach to theory structure.[8] This alternative (or cluster of alternatives) has been dubbed the "semantic conception," the "nonstatement view," and the "models approach" to scientific theories. I will refer to it as the model model (MM).[9] MM was developed in part in response to criticisms of the sort discussed on page 58. MM offers a less restrictive framework for representing the nonformal patterns exhibited by theories but ultimately provides little guidance in characterizing and understanding these nonformal patterns.

### *Theories and models*

The different versions of MM share a core commitment to viewing theories as an abstract specifications of a class of models.[10] The term "model" is notoriously ambiguous; meaning a representation or simulation (a scale model, map, or computer program), an abstraction (as in some mathematical models), an analogue (Bohr's planetary model of the atom), an experimental organism (as in the adult male Sprague–Dawley rat) or an experimental preparation (such as the amphetamine model of schizophrenia).

According to MM, a model is a structure that satisfies (i.e., renders true) a theory. The relationship between theories, models, and the real systems in the world can be understood as follows:

(i) *Theories* specify or define abstract or idealized systems.
(ii) *Models* are the structures that satisfy (or instantiate) these specifications or definitions (the abstract and idealized system is itself a model of the theory).
(iii) These models are more or less similar to, or homomorophic, with *real systems*, and so could be used to control and predict real systems if the real systems were sufficiently similar to the model.[11]

### *Theories as extralinguistic structures*

Central to MM is the idea that theories are abstract extralinguistic structures quite removed from the phenomena in their domains. Theories are not identified with any particular representation. In this way, MM accommodates the diverse conventions for communicating theories in the wild (p. 58) as well as the mathematical structures that often compose theories (p. 59). Models may be partial, as are the diverse representations of the $Na^+$ channel, and they may very well be incomplete, giving MM a flexibility not available within the inferential strictures of the ORV. MM is motivated in part by its ability to accommodate the varied structures and states of completion of theories in the wild (Beatty, 1981; Beth, 1949; Lloyd, 1988; Suppe, 1977; van Fraassen, 1980, pp. 64–5).

### *Abstraction and idealization*

According to MM, theories typically are not isomorphic to any real system; instead, they are more naturally thought of as homomorphic with, as replicas of (Suppe, 1989), or as similar to (Giere, 1999), real systems. Theories (and their models) are typically abstract and/or idealized. Theories are abstract to the extent that they describe real systems in terms of only a few of their relevant parameters, assuming that all others impact negligibly on the behavior of the system (Suppe, 1989, pp. 94–5). Theories are idealized if it is physically impossible for the real system to take on the allowable values of the parameters (e.g., point masses or frictionless planes).

On Suppe's counterfactual account of the relationship between theories/models and real systems, theories and models are *replicas* of real systems (Suppe says "phenomenal systems"). Replicas describe what a real system *R* would be like if it were isolated from the disturbing influence of parameters not included in the model *M* (Suppe, 1989, p. 95). Abstract models satisfy this requirement, since it is physically possible that *R* satisfy the conditions specified in *M* (perhaps under extreme experimental conditions). Idealized models satisfy this counterfactual requirement since the antecedent is physically impossible.[12] This counterfactual formulation is one means by which advocates of MM hope to sidestep the ORV's problems concerning laws of nature (p. 62).

## *MM, theories, and laws of nature*

Suppe (1989) describes three varieties of laws appearing in scientific theories: laws of coexistence, laws of succession and laws of interaction.[13] Each of these may be deterministic or statistical. Laws of coexistence, such as the Boyle–Charles gas law, specify possible positions in the state space by describing equations fixing possible overall states of the system. Laws of succession, such as Newton's laws of motion, specify possible trajectories through the state space and so specify how the system, left to itself, will change over time. Finally, laws of interaction, specify the results of interaction between two or more systems, such as the interaction of a particle with a measuring device. These laws together define the class of models of the theory.

Advocates of MM split on the empirical status of both scientific theories of laws. Suppe's counterfactual account treats theories as empirical commitments as to how some real system would work if the abstracted variables were the only determinants of its behavior or if the idealizing conditions were met. Others – Beatty (1981), Giere (1999) and van Fraassen (1980) – see theories as definitions; theories define a class of models, and the empirical claims of science, as Beatty puts it, "are made *on behalf of* theories" (1981, p. 400, emphasis in original), asserting that some (type of) real system is an instance(s) of the kind of system defined by the theory (Giere, 1999, ch. 5).

These accounts are each motivated by difficulties with ORV-style laws (concerning scope, abstraction and idealization). The accounts differ as to whether theories express empirical commitments. On each account, questions about scope and universality are seen as external questions about the relation between a theory and the phenomena in its domain, questions to be answered by experiment and auxiliary hypotheses. This is a useful suggestion, since preoccupation with universality and unrestricted scope distracts attention from the fact that theories often have limited domains. Because theories are abstract and idealized, they typically do not apply universally. Abstract theories apply only to real systems for which the influence of extraneous variables is negligible; idealized theories literally have a scope of zero.

Each of these MM approaches to laws provides tools to grapple with issues of universality, scope, abstraction, and idealization. Suppes' approach is *prima faciea* more appealing because it sustains the reasonable claim that theories express empirical commitments. Neither approach clarifies the necessity of laws. Giere (1999, p. 96) suggests that the necessity of laws statements should, like issues of scope, be considered external to theories. This suggestion is unattractive primarily because many uses of theories (including explanation, control, and experimental design) depend crucially upon notions of necessity; an account of theories cannot cavalierly dismiss problems with laws precisely because laws (or something else filling their role) are so crucial to the functions of theories in science.

### *MM and the nonformal structures of scientific theories*

In a recent elaboration of MM, Schaffner argues that most theories in the biomedical sciences (e.g., the clonal selection theory of immunology) are typically "overlapping interlevel temporal models" of less than universal scope (1993a, ch. 3). In doing so Schaffner is the first to clearly recognize and explore this prevalent nonformal structure of theories in the biological sciences. He terms these theories "theories of the middle range" (1993a) and shows how they can be accommodated within MM; see also Suppe (1989, ch. 8). Schaffner's "models" are essentially the same as those described above. These models have nonuniversal domains, and they are typically constructed around different "standard cases" or "experimental models" that serve as prototypes and are all more or less similar to one another (hence "overlapping"). Schaffner also recognizes a temporal component to the organization of these theories; they depict temporal pathways of sequential events related by generalizations. Finally, these theories are "interlevel" in that they include entities at different Oppenheim and Putnam-style levels. Schaffner (1993a) is a hair's breadth away from recognizing that many theories are multilevel descriptions of mechanisms; he then toys with this idea (Schaffner, 1993b).

MM avoids some of the criticisms of the ORV, especially those problems relating to representational flexibility, the abstraction and idealization of theories, and perhaps problems with laws of nature. Yet, the added abstraction of MM renders it even less informative than the ORV about nonformal patterns in theories in the wild.

## Mechanisms: Investigating Nonformal Patterns in Scientific Theories

While MM accommodates nonformal patterns better than the ORV, it does little to highlight or motivate the search for them. Attention to nonformal patterns provides important resources for understanding how theories are built and the diverse kinds of explanations that scientific theories provide. Consider one kind of theory, theories about mechanisms, and notice how the nonformal patterns of such theories are used in the construction, evaluation, and revision of theories over time.

## *Mechanisms and their organization*

Mechanisms are entities and activities organized such that they realize of regular changes from start or setup conditions to finish or termination conditions (Wimsatt, 1976; Bechtel and Richardson, 1993; Glennan, 1996; Machamer et al., 2000, p. 2). Entities are the objects in mechanisms; they are typically described with nouns in linguistic representations. Activities are what these entities do; they are typically described with verbs or depicted with arrows. Together, these component entities and activities are organized to do something – to produce the *behavior of the mechanism* as a whole, to use the term suggested by Glennan (1996); behaviors are the "regular changes" that mechanisms realize.[14]

Types of mechanisms can be individuated on the basis of their overall behavior, their component entities and activities, or the way the components are organized. First, mechanisms can differ behaviorally – by the phenomena that they realize. In specifying the behavior of a mechanism, one immediately constrains the entities, activities, and organizational structures that are relevant to that behavior, and so places a global constraint on the search for the mechanism. Mechanisms can also be individuated by the (kinds of) entities and activities that constitute their components. Finally, mechanisms can be individuated by their active, spatial, and temporal organization. A mechanism's *active organization* includes activities and interactions (excitatory and inhibitory) of the mechanism's component entities (Wimsatt, 1974; Craver, 2001). S*patial organization* includes the relative locations, shapes, sizes, orientations, connections, and boundaries of the mechanism's entities. Finally, a mechanism's *temporal* organization includes the orders, rates, durations, and frequencies of its activities (Craver and Darden, 2001).

Consider this example. The voltage sensitive $Na^+$ channels in Trumpler's (1997) discussion are crucial components in the mechanism for producing action potentials, the electrical waves propagated as signals through neurons (this is the behavior of the mechanism as a whole). Neurons are electrically polarized at their resting membrane potential (approximately –70 mV). The intracellular fluid is negatively charged with respect to the extracellular fluid because of differences between intracellular and extrecellular ion concentrations. Depolarization is a positive change in the membrane potential. Neurons depolarize during an action potential when voltage-sensitive $Na^+$ channels open, selectively allowing $Na^+$ ions to flood the cell, thereby spiking the membrane potential (peaking at roughly +50 mV). One plausible mechanism for the activation of the $Na^+$ channel is represented in Figure 4.1 (drawn from Hall's (1992) verbal description).

Here is how the mechanism works (shown in the bottom panel). First, a small initial depolarization of the membrane (resulting from chemical transmission at synapses or spreading from elsewhere in the cell) repels the evenly spaced positive charges composing the α-helix. Second, the alpha helix rotates in each of the four protein subunits composing the channel. The rotation of the helix changes the conformation of the channel, creating a pore through the membrane. Third, the pore is lined with a "hairpin turn" structure containing charges that select specifically $Na^+$ ions to flow into the cell by diffusion. This panel depicts the mechanism's active and temporal organization; it shows an orderly sequence of steps (repelling, rotating, opening, and diffusing), each systematically dependent on, and productively continuous with, its predecessor.

The top pannel depicts the set-up conditions for this mechanism, including the relevant entities ($Na^+$ ions, α-helices, hairpin turns), their relative sizes, shapes, positions, locations (e.g., the channel spans the membrane, and $Na^+$ ions fit through the pore), and the connections, compartments, and boundaries between them. Not represented in the diagram are such factors as temperature, pH, and the relevant ionic concentrations. Such factors are the background or standing conditions upon which the behavior of the mechanism crucially depends. Figure 4.1 thus nicely illustrates the active, spatial, and temporal organization of the components in the mechanism of $Na^+$ channel activation, but it nonetheless abstracts from several crucial parameters for the working of the mechanism.

### *Mechanism schemata*

Mechanistic theories are mechanism schemata. Like MM-theories, mechanism schemata are abstract and idealized descriptions of a type of mechanism. They describe the behavior of the mechanism, its component entities and activities, their active, spatial, and temporal organization, and the relevant background conditions affecting the application of the theory. The scope of mechanism schemata can vary considerably, from no instances (for idealized descriptions) to universality, and any point between.

### *Levels*

Mechanism schemata often describe hierarchically organized networks of mechanisms nested within mechanisms. In such schemata, higher-level activities ($\psi$) of mechanisms as a whole ($S$) are realized by the organized activities ($\phi$) of lower-level components ($X$s), and these are, in turn, realized by the activities ($\sigma$) of still lower-level components ($P$s). The gating ($\sigma$) of the $Na^+$ channel ($P$) is part of the mechanism ($X$) for generating action potentials ($\phi$), which is part of almost every brain mechanism involving electrical signals. The relationship between lower and higher mechanistic levels is a part-whole relationship with the additional restriction that the lower-level parts are components of (and hence organized within) the higher-level mechanism. Lower level entities (e.g. *X*s) are proper parts of higher-level entities (*S*), and so the *X*s are no larger, and typically smaller, than *S*; they are within *S*'s spatial boundaries. Likewise, the activities of the lower-level parts are steps or stages in the higher-level activities. Exactly how many levels there are, and how they are to be individuated, are empirical questions that are answered differently for different phenomena (Craver, 2001).

Mechanistic hierarchies should not be confused with intuitive ontic hierarchies, which map out a monolithic stratigraphy of levels across theories, entities, and scientific fields. Mechanistic hierarchies are domain specific, framed with respect to some highest system *S* and its $\psi$-ing. The parts in mechanistic hierarchies are components organized (actively, spatially, temporally, and hierarchically) to realize the behavior of the mechanism as a whole. This distinguishes mechanistic wholes from mere aggregates (such as piles of sand), mere collections of improper parts (such as the set of 1-inch cubes that compose my dog, Spike), and mere inclusive sets (such as the albums in the Clash discography). There are no doubt many senses of "level" that are not sufficiently distinct in the philosophical literature. Sorting them out is an important and unresolved project in the philosophy of science (Simon, 1969; Wimsatt, 1974; Haugeland, 1998).

## *Varieties of mechanisms*

Both the ORV and MM are pitched too abstractly to capture recurrent nonformal patterns exhibited by mechanism schemata: patterns in the organization of mechanisms that are crucial for understanding how these theories explain and how they are constructed over time. Consider one branch in a possible (nonexclusive) taxonomy of mechanisms.

Begin with *etiological mechanisms* and *constitutive mechanisms* (Shapere, 1977; Salmon, 1984, ch. 9). Etiological mechanisms (such as natural selection) include the organized entities and activities antecedent to and productive of the phenomenon to be explained (e.g., the mechanism by which a trait comes to be fixed in a population). Constitutive mechanisms (like the mechanism of $Na^+$ channel gating) realize (rather than produce) higher-level phenomena; these higher-level phenomena are contemporaneous with (rather than subsequent to) and composed of (rather than produced or effected by) the organized activities of lower-level components.

Etiological mechanisms include both *structuring mechanisms* and *triggering mechanisms.* Dretske (1995) has distinguished "structuring causes" from "triggering causes," on the grounds that the triggering cause *T* completes a set of otherwise insufficient preexisting conditions *C* thus making ($T + C$) a sufficient cause of the explanadum event or phenomenon *E*. For example, spreading depolarization (*T*), given the $Na^+$ channel setup (*C*), triggers the opening of the channel (*E*). A structuring cause *U*, in contrast, prepares the conditions *C* within which

*T* can be a triggering cause and so produces the mechanism linking *T* and *C* (1995, p. 124). For example, one may perhaps look to evolutionary theory to explain how the sodium channel came to activate under conditions of slight depolarization. In triggering mechanisms, *T* in *C* is sufficient for *E*; in structuring mechanisms, *U* produces the mechanism by which *T* is sufficient for *E*.

Two etiological varieties of structuring mechanisms are *selective* and *instructive mechanisms*. In selective mechanisms, a population of variants is produced (relatively) independently of environmental influences and then, by virtue of some critical environmental factor, the set of variants is changed such that certain traits are increasingly represented in the population. Examples of selective mechanisms include evolution by natural selection, clonal selection for antibodies in immunology, and perhaps neural Darwinism; each is discussed in Darden and Cain (1989). Instructive mechanisms (such as inheritance of adaptive acquired characteristics or pedagogy) are different in the first stage, since the production of adaptive variants is directly influenced by features of the population's environment.

Different types of mechanisms can be distinguished on the basis of recurrent patterns in their organization. Mechanisms may be organized in series, in parallel, or in cycles. They may contain branches and joins, and they often include feedback and feedforward subcomponents. Some mechanisms are redundantly organized, and some have considerable capacity for reorganization or plasticity in the face of damage. These recurrent patterns in mechanistic organization have been investigated by Wimsatt (1986), but there remains considerable work to be done in sorting out the axes along which mechanisms and schemata might differ.

Scientific theories exhibit a variety of patterns in domains of empirical phenomena, patterns that are invisible if one abstracts too far away from the details of scientific theories in the wild. Attention to these details pays dividends for understanding mechanistic explanation (next section) and the process of building multilevel mechanism schemata (p. 72).

## *Mechanistic explanation*

Mechanism schemata explain not by fitting a phenomenon into a web of inferential relationships but by characterizing the mechanism by which the phenomenon is produced or realized. This suggestion is consistent with the MM-related account of explanation as pattern completion, or prototype activation (Giere, 1999, ch. 6; Churchland, 1989), but insists, in addition, on an explanatory role for the nonformal patterns in these theories. Not all patterns are explanatory; one goal is to distinguish those that are from those that are not. Salmon (1984) has suggested that at least one important kind of kind of explanation involves tracing pathways in a causal nexus; a phenomenon is explained by showing how that phenomenon fits into a pattern of causal processes and their interactions. Mechanistic patterns are further distinguished by their active, spatial, temporal, and hierarchical organization; and these features of mechanism schemata draw our attention to salient features relevant to the intelligibility provided by a description of a mechanism.

Scriven (1962) emphasizes the narrative structure of many explanations. There are no good stories without verbs. The verbs the $Na^+$ channel schema include "repelling," "rotating," "opening," and "diffusing." Verbs provide the productive continuity in the mechanism, intelligibly linking earlier stages to later stages. Substantivalists in the philosophy of science have emphasized static structures, occurrent events, entities and relations over dynamic activities, extended processes, changes and forces. Substantivalists nominalize or neglect active features of scientific ontology, the diverse kinds of changing that underlie regularities; they leave out the verbs. This neglect can be redressed with attention to types of activities, criteria for their individuation, and the differences between the scientific investigation of activities and entities (Machamer et al., 2000).

Emphasizing the importance of activities in mechanisms cannot sidestep the problems with laws of nature discussed on pages 62 and 67. An adequate account of mechanism schemata must await an account of how activities are different from mere regularities. Some progress on these problems will be gained by exploring the connections between the mechanistic perspectives on theory structure sketched here and recent work on laws (Lange, 1995; Roberts, 1999), invariant generalizations (Woodward, 1997), physical causality (Dowe, 1992), capacities (Cartwright, 1989; Glennan, 1997), and the pragmatics of laws (Mitchell, 2000). A fresh perspective might be provided by investigating the practices of scientists as they introduce, individuate, characterize, and describe the activities picked out by the verbs in mechanism schemata.

## *Constructing mechanism schemata*

Attention to the nonformal patterns exhibited by theories has already yielded dividends in thinking about theory construction. For example, Bechtel and Richardson (1993) discuss decomposition and localization as research strategies in the construction of mechanistic theories. Craver and Darden (2001) have extended this work, showing that the construction of mechanism schemata typically proceeds gradually and piecemeal by revealing constraints on the mechanism, constraints from the behavior of the mechanism, the available entities and activities for the mechanism, and features of their active, spatial, temporal, and hierarchical organization. Finding such empirical constraints prunes the space of plausible mechanisms and often suggests potentially fruitful avenues for further research.

One goal in constructing a description of a mechanism is to establish a seamless productive continuity of the mechanism, without gaps, from beginning to end. In pursuit of this goal, researchers frequently forward chain, using known stages early in the mechanism to conjecture or predict stages that are likely to follow, and backtrack, using known stages late in the mechanism to conjecture or predict the entities, activities, or organizational features earlier in the mechanism. Nonformal aspects of theory structure are used by scientists to generate new hypotheses and to target the praise and blame from empirical tests at specific portions of the theory (Darden and Craver, 2001).

A second goal in constructing specifically multilevel mechanism schemata is to integrate the different levels together into a description of one coherent mechanism. *Interlevel integration* involves elaborating and aligning the levels in a hierarchy to show, for some *X*'s $\phi$-ing

(i) how it fits into the organization of a higher level mechanism for *S*'s $\psi$-ing, and
(ii) how it can be explained in terms of the constitutive mechanism (the organized $\sigma$-ing of *p*s).

These levels are linked together through research strategies that exhibit the constitutive causal relevance of lower level organized entities and activities to higher level entities and activities. In this way, upward looking and downward looking research strategies combine to provide an integrated description of the pattern exhibited by a multilevel mechanism (Craver, 2001).

## Conclusion

Scientific theories have many different structures, structures that exhibit patterns in diverse domains of phenomena. Inferential patterns are crucial to understanding some aspects of science and the way that it changes over time. But there is a great deal more to be said about these patterns than can be said by assimilating them to an inferential pattern. Nonformal patterns (such as mechanistic patterns) are also important for understanding how theories are used and constructed. Closer scrutiny of the diverse structures of scientific theories, especially mechanistic patterns, is likely to pay serious dividends for understanding science and scientific practice.

## Notes

1 Thanks to Lindley Darden, Peter Machamer, and Ken Schaffner for their time and help.

2 Patterns can be understood, following Dennett (1991), either in terms of their ability to be recognized or in terms of their susceptibility to expression in something less than a "bit map"; see also Haugeland (1998); Toulmin's (1953) discussion of maps is in many ways similar to this notion of a pattern). A "domain" following Shapere (1977) is some body of items of "information" variously interrelated in a way that helps one to solve an important problem that science is ready to tackle at a given time (Shapere, 1977, p. 525).

3 Classic statements of the ORV can be found in Braithwaite (1953), Carnap ([1939] 1989), Duhem (1954), Hempel (1965, chs 4 and 8; 1966, ch. 6) and Nagel (1961, chs 5 and 6). Valuable critical expositions include Suppe (1977, 50–1; 1979; 1989) and Thompson (1989, chs 2 and 3). The ORV was developed primarily for the expression of physical theories, but it has been applied with debatable success to evolutionary biology and/or population genetics (Braithwaite, 1953; Hull, 1974; Ruse, 1973; Williams, 1970), and psychology (Skinner, 1945).

4 This inferential approach to scientific theories has been dubbed the "received" (Putnam, 1962) or "orthodox" (Feigl, 1970) view, the "statement view," the "syntactic conception" (Thompson, 1989), the "hypothetico-deductive" account (Lloyd, 1988), "the Euclidean ideal" (Schaffner, 1993a,b), and the "sentential" or "propositional" account (Churchland, 1989). I call it the ORV to flag its waning hold on the philosophy of science and to avoid enshrining in a name a single interpretation of either the ORV or of its shortcomings.

5 This image of theory structure was inspired at least in part by Russell and Whitehead's efforts to reduce mathematics to logic.

6 Some object to theory-centered approaches to the philosophy of science generally. Among these, "Globalists" focus on more inclusive units of analysis than theories, recommending such alternatives as disciplinary matrices or paradigms (Kuhn, 1962), fields (Darden and Maull, 1977; Darden, 1991), practices (Kitcher, 1993, p. 74), research programs (Lakatos, 1970), and traditions (Laudan, 1977). These global units of science include, in addition to theories, also experimental techniques, institutional practices, consensual standards and norms, organizations, and worldviews. "New Experimentalists," on the other hand, decenter theories in the analysis of science and center experimentation instead (Hacking, 1983; Galison, 1987; Rheinberger, 1997). Still others, with primarily epistemological concerns, have criticized correspondence rules, the theory/observation distinction, and the tenability of scientific realism (Achinstein, 1968; Putnam, 1962; Schaffner, 1969; van Fraassen, 1980). Suppe (1977) is the definitive history of this line of criticism.

7 One response to this line of criticism, one pursued by Waters (1998), is to argue that philosophers have mistakenly confused universal causal regularities with distributions (claims about how a trait or property is distributed across a population of organisms). One way of putting this is that the law $(x)(Fx \supset Gx)$ is true of everything (a universal causal generalization), although only some things satisfy the antecedent (a distribution).

8 Important statements and elaborations of the model model include Beth (1949), Giere (1979; 1988), Schaffner (1993a), Suppe (1977; 1989), Suppes (1967), and van Fraassen (1980). Beth (1949) applied this approach to Newtonian and quantum mechanics, and it has been worked out for theories in classical mechanics (McKinsey and Suppes, 1953), quantum mechanics (van Fraassen, 1991), evolutionary theory and population genetics (Beatty, 1980; 1981; Lloyd, 1988, ch. 2; Thompson 1989, ch. 5), sociobiology (Thompson, 1989), biological taxonomy (Suppe, 1989, ch. 7) and most recently, declarative memory and synaptic mechanisms in neuroscience (Bickle, 1998).

9 There is no consensus on how to draw the contrast between the ORV and MM. The most common approach relies on the distinction between syntax and semantics, a distinction that hardly clear in its own right and one that has been difficult to apply neatly

to ORV and MM. Another contrast is between ORV as a "statement view" of theories and MM as a "nonstatement view," but statements can be models and the components of the ORV might be reasonably interpreted as propositions rather than statements. Some have argued that anything representable in the ORV can be represented in MM and vice versa, minimizing the motivation to spell out the differences in detail. Little of significance has turned on getting this distinction right.

10 There are two classic formulations of MM: a *set theoretic formulation*, recommended by Sneed (1971), Stegmüller (1976), and Suppes (1967), according to which theories are structures represented by set theoretic predicates that define a class of models; and a *state-space approach*, favored by Beth (1949), Suppe (1989) and van Fraassen (1980), according to which theories are constraints on multidimensional state-spaces or configurations of sets of such spaces which define a class of models. Debates over the relative merits of these approaches can be safely neglected for present purposes (van Fraassen, 1972; Suppe, 1979).

11 I neglect a fourth element, a "phenomenal system" (Suppe, 1989) or an "empirical model" (Lloyd, 1988) that is constructed on the basis of data and intermediate between models and real systems.

12 This suggestion, if I understand it correctly, has the strongly counterintuitive consequence of rendering all idealized stems models of any given real system.

13 Suppe (1989) also includes laws of quasi-succession.

14 On one reasonable interpretation of this realizing relationship – modified from Kim (1995), discussing Lepore and Loewer (1987) – a mechanism *M* composed of the actively, spatially, and temporally organized $\phi$-ing of *X*s realizes *S*'s $\psi$-ing just in case

(i) it is physically impossible of *S*'s $\psi$-ing to differ without there being some difference in *M*, and
(ii) S's $\psi$-ing is exhaustively explained by *M* (in an ontic and not necessarily epistemic sense).

This way of spelling out the realization relationship differs in that it specifies more precisely the character of the organizing relationships involved in realizing a higher-level phenomenon.

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