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Metaphysical Dependence: The Role of Mathematical Structure in Physical Modality

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Metaphysical Dependence: The Role of Mathematical Structure in Physical Modality

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Metaphysical Dependence: The Role of Mathematical Structure in Physical Modality

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I develop a novel metaphysical theory of the modal structure of the physical world, which has important consequences for debates regarding laws of nature, scientific explanation, the nature of physical properties, and the applicability of mathematics to science. The theory holds that modal properties of the physical world metaphysically depend on properties of mathematical structures. I show that the relation of metaphysical dependence is naturalistically acceptable by offering examples of non-causal scientific explanation that tacitly make use of such a notion. My view offers a non-Humean understanding of nomological necessity, a unification of the epistemology of modality with the epistemology of mathematics, and an explanation of the success of mathematics in predicting and explaining empirical phenomena.

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1. Methodological Naturalism in Metaphysics

1.1. Laws of nature, causation, properties, and modality

The world is fundamentally a modal place. Physical systems have modal properties, and laws of nature have the force of nomological necessity. Special relativity tells us that material bodies cannot go faster than the speed of light. The first law of Thermodynamics says that matter cannot be created or destroyed. The Heisenberg Uncertainty principle tells us that a particle cannot simultaneously have a definite location and a definite momentum. If we are committed to the content of our best scientific theories, we must accept that nature of the physical world is inherently modal. Causality, equilibrium, laws of nature, and probability are four modal notions that feature prominently in scientific theory and explanation. These modal properties are necessary to make sense of our best scientific theories, and no scientific realist can do without them. But how is the scientific realist to account for modality? In the vein of structural realists Ladyman and Ross, many suggest that this modal structure is primitive. I offer a new account in which the modal structure of the physical world is metaphysically dependent upon mathematical structure.

This chapter lays the groundwork for the naturalistic methodology that is used throughout the dissertation. This includes the criteria by which metaphysical theories will be judged, such as theoretical unification and explanatory power, and a discussion of a notion of mathematical structure adapted from Wolfgang Spohn.

The next chapter explores the relationship between laws of nature and modal physical structure through a case study in a posteriori necessity. I argue that we cannot determine the metaphysical status of non-fundamental laws of nature without knowing the structural features of the substances and properties they describe. I consider Bird's (2007) argument that, necessarily, salt dissolves in water, and I defend it against several contingentist objections. I conclude that some higher-level laws describing the behaviors of molecular compounds are necessary due to their supervenience on underlying physical structures. I suggest that such necessity is likely commonplace among laws of nature in the special sciences.

In Chapter 3, I show why the scientific realist must be committed to an objective, metaphysically robust account of the modal structure of the physical world. I argue against Humean regularity theory on the grounds it is incompatible with scientific realism and fails to be naturalistically motivated. I specifically address the Mill-Ramsey-Lewis view, which states that laws of nature are those regularities that feature as axioms or theorems in the best deductive system describing our universe. I argue that this view, also known as sophisticated Humeanism, is flawed in three significant ways: One of its central concepts cannot be formulated non-circularly, it cannot offer a satisfactory account of the laws of the special sciences, and it can offer no explanation of the success of inductive inference. I address several ontological difficulties that are difficult to square with Humeanism's empiricist motivations, and I conclude by echoing Maudlin's (2007) claim that without the commitment to Hume's epistemological and semantic views we have little reason to be Humean about the laws of nature.

In Chapter 4, I raise objections to dispositionalist accounts of physical properties, such as causal structuralism. Causal structuralism is the view that the casual profile of a property exhausts its individual essence. The view purports to offer a metaphysical account of all physical properties, but the view fails to account for the higher-order mathematical properties of certain physical properties. Since these higher-order properties play an indispensable role in contemporary physical theory, this is an unacceptable shortcoming. I argue that what is needed is a structuralist view of properties that is not merely causal but that incorporates higher-order mathematical properties into the identity conditions of physical properties.

In Chapter 5, I put forth my positive view on the modal structure of the physical world. I argue, by way of analogy between the no-miracles argument for scientific realism and the indispensability argument for mathematical realism, that we must posit a relation of metaphysical dependence between mathematical structure and modal physical structure. The extended indispensability argument and cases supporting it show that facts about mathematical structures and relations can explain and predict certain features of the physical world. Specific cases discussed include the hexagonal structure of honeycomb, the prime-numbered life cycles of the North American Magicicada, and the Glashow-Weinberg-Salam model of the electroweak force. Just as no-miracles is taken to be an argument for theoretical entities and a dependence relation (usually causal), indispensability must similarly be taken to be an argument for a dependence relation between explanans and explanandum. I suggest that this relation is one of metaphysical dependence. I show this relation to be naturalistically acceptable by offering examples of non-causal, scientific explanation that implicitly make use of such a notion. Examples include the Lorentz-invariance of spacetime explaining the phenomenon of time dilation and the curvature of spacetime explaining the curved paths of objects in spacetime. I conclude by speculating about issues on which my view of physical modality sheds light, such as the applicability of mathematics to the sciences and the usefulness of computer simulations in modeling counterfactual scenarios.

1.2. Methodology and Assumptions

I largely accept the view of the role of metaphysics that Ladyman, Ross, Collier, and Spurret (2007) present in their introductory chapter “In Defense of Scientism.” Whereas methodological naturalists have often favored the positivist view that science leaves no room for metaphysics, LRCS defend a verificationist approach that is inspired by Piercian pragmatism. As they see it, the difference between positivism and pragmatism is that, for Positivists, the point of the verification principle was to exclude metaphysics, whereas for the Pragmatists it was to apply to metaphysics. By appealing to the historically successful institutional standards of science, LRCS, carve out a science-friendly understanding of the role of metaphysics as unifying hypotheses and evaluating consilience relations among the sciences.

Radical methodological naturalists, LRCS argue, should contend that there is a 'reasonable and significant' job for metaphysicians to do, because one of the important things we want from science is a relatively unified picture of the world. This norm of unification is neither arbitrary nor known a priori; it is supported by the history of science. Scientists tend not to pose or accept hypotheses that are "stranded from the otherwise connected body of scientific beliefs." LRCS take this fact to reflect the important justificatory role that is played by a hypothesis's standing in "reciprocal explanatory relationships – networked consilience relationships – with other hypotheses" (27). Evaluating global consilience networks of relations among scientific theories and hypotheses is a necessary task that is not delegated to any particular scientific discipline (due in part to efficiency constraints and the need for disciplinary specialization). This is where the metaphysician comes in. Working in concert with science and scientific knowledge, metaphysicians can propose and evaluate theoretical unification strategies within or across scientific disciplines. "Metaphysics, as we will understand it here, is the enterprise of critically elucidating consilience networks across the sciences" (28). This view, while not hostile to the possibility of metaphysics, certainly presents a far more restricted conception of the metaphysician's domain than the one that is traditionally accepted within analytic philosophy.

Another tenet of the view is that science is a collective enterprise, distinguished from non-science by its institutional norms and filters. These include requirements that claims undergo rigorous peer review before "being deposited in serious registers of scientific belief" as well as requirements governing representational rigor with respect to theoretical claims and accounts of observations and experiments. Again, these norms are neither arbitrary nor is the fact that they hold merely a historical accident. They are justified by the fact that, while "humans beings are poorly prepared by evolution to control complex inductive reasoning across domains that did not pose survival problems for our ancestors," we can achieve "significant epistemological feats by collaborating and by creating strong institutional filters on errors." Science is characterized by our set of institutional error filters that have proven effective in guiding the discovery of the objective character of the world. Because of science's success in this endeavor, a naturalistic metaphysics must be compatible with the practices and aims of science and should be as non-revisionary as possible. Let us now turn to the tenets of the particular brand of naturalism with which I'll be working.

One of the most important tenets of methodological naturalism involves taking science at face value. This includes the special sciences. What is the difference between fundamental and special sciences? I accept Ladyman and Ross's view that the two are differentiated, in part, by their domains. Fundamental physics is the science to which measurements taken anywhere in the universe are relevant. Special sciences, on the other hand, consider data from only certain sub-regions of spacetime. Chemists, for instance, may consider data from any region of spacetime that is occupied by chemical elements, while only areas of spacetime in which natural selection has had a chance to operate are of interest to the biologist. Measurements that are relevant to neuroscience are those taken in the regions of spacetime occupied by brains, and measurements from elsewhere in the universe cannot impugn the generalizations to which current neuroscience is committed.

Another way to formulate the distinction between fundamental physics and the special sciences – intimately connected to the notion of domain – is in terms of *scale*. Different sciences study the world at different spatio-temporal scales. Fundamental physics describes the world at all scales (and considers measurements taken at all scales), while the special sciences describe the world at restricted scales. As such, the laws, patterns, and objects studied by the special sciences are only available at the scales of measurement of the special sciences. If we want to talk about the things studied in astronomy – stars, planets, moons, galaxies – it only makes sense to consider certain spatio-temporal scales of measurement; Kepler's laws of planetary motion, for instance, are applicable at spatial scales of 10^{12} to 10^{15} meters. GDPs exist only across spatial scales large enough to include countries and temporal scales of enough duration for trade to occur. Under this characterization of special sciences as those sciences to which only measurements from restricted areas of the universe are relevant, it is certainly the case that some areas of physics come out as special sciences. The physics of optics has as its potential domain of study any part of the universe that contains light. Classical mechanics is only accurate for the scales at which matter exists.

While some physical theories have domain-restrictions, others have none. Special relativity, for instance, dictates that nothing can travel faster than the speed of light, and this claim is to be understood as a universal one – it is not relativized to any region or scale of the universe. That the generalizations of fundamental physics apply at every spatio-temporal scale is what accounts for its fundamentality. Ross and Ladyman write, "Vulnerability to counterexamples from anywhere is the basis on which we have defined 'fundamental' physics, and it is restriction of scope of its generalizations that defines a science as 'special'." (283) We might make an addendum to the LRCS view that allows for a further ordering of theories bearing the fundamentality relation in terms of derivability. Thus, when derive the tenets of special relativity from some further underlying unifying structure, we can consider the unifying structure more fundamental.[1]

This characterization of the special sciences, when combined with a naturalistic commitment to realism about the special sciences, leads us to the metaphysical postulate of the *scale-relativity of ontology.* The scale-relativity of ontology is the thesis that claims about what (really, mind-independently) exists should be relativized to (real, mind-independent) scales at which nature is measureable. Unlike LRCS, I am not committed to the claim that there can be no unified ontology of the world and that all ontological claims must be relativized to a scale, as one could make the general ontological claim that what exists relative to some scale exists simpliciter. Rather, I find the value of scale-relativity of ontology to be in the reminder that the world is interestingly structured at many scales, and we ought not expect our ontology to be bound to any one of them.

Scale-relativity of ontology walks the line between reduction and emergence.

[1] Ladyman and Ross are silent on the question of whether there is a most fundamental 'level' of reality, and I do not address that question here.

Special sciences describe the world at particular scales and aim at discovering laws that govern the structures evident at those scales. Because there are empirically interesting structures that arise at macroscopic scales and are not clearly derivable from or characterizable in terms of underlying structures, we should not expect the special sciences to be fully reducible to more fundamental sciences or to fundamental physics. Part of respecting the autonomy of the special sciences involves accepting that the truth-makers of the claims of some special science will be objects in the domain and at the scale of that special science. Thus, we should not take micro-scale fundamental physical objects such as collections of quantum particles to be the truth-makers of, for instance, biological claims. For some special sciences, it is not even clear how we could understand their claims as being about collections of microscopic particles.

Consider the decision-theoretic structure of a rational bet, for instance, a bet on a fair coin toss that costs one dollar to play and pays out three dollars if the coin lands heads up. Is there any meaningful sense in which the structure of this choice reduces to anything in physics, or even to anything in chemistry or biology? It seems to me that it does not. Yet it still describes a feature of the physical world, namely the modal structure of one type of rational bet. As the data that characterize rational betting are compressible and we can predict future outcomes based on features of rational bets, we ought to have no qualms about including rational bets in our ontology. Doing so does not commit us to mysteriously emergent metaphysical substances, though it may well commit us to sui generis modal structures. Since I will later argue that the modal structures of the physical worlds metaphysically depend on mathematical structures, and that naturalists already have reason to be realists about mathematical structures, this should not be taken as an additional burden for the metaphysical naturalist.

Further, commitment to sui generis modal structures at macro scales should not be taken to conflict with the unity of the sciences. Along with LRCS, I accept that there are instances of Nagelian reductions of one branch of a science to another in the style of reducing thermodynamics to statistical mechanics. However, since this reduction employs a number of idealizations that are not always strictly true[2], we should not take it to be a strong reduction in the ontological sense. At the same time, the existence of such reductions and theoretical unifications tell against strong emergentism. There is no evidence that genuinely new metaphysical substances emerge that are not physical in even the broadest sense of the word. By the broadest sense of the word "physical" I mean to include anything that is detectable by measurement or observation, or inferable by IBE, or that can be used to reliably predict things that can be measured or observed.

Someone in my position might be tempted to stave off strong emergentism by appealing to the metaphysical composition relation. One might emphasize the fact that all objects in any special-science domain are composed of fundamental physical objects such as quantum particles or fields. I neither accept nor deny this claim. Like LRCS, I am skeptical that there is a unified metaphysical composition relation and prefer to talk about composition pluralistically, in terms of the notions of composition that are employed within the various special sciences. Plasma physics tells us when charged particles compose a plasma, chemistry tells us when atoms compose an element, and molecular biology has the authority to say when proteins compose a cell. It is not obvious to me that there can or should be a unified notion of composition that can cut across all of the special sciences, nor does it seem to me that the lack of such a notion poses a problem to the unity of science or relations of fundamentality among the sciences.

I am somewhat less skeptical of the standard metaphysical supervenience relation, and I do not have a problem with the claim that some features of the macro world supervene on features of the micro. It seems to me that once the underlying structures and patterns of matter and energy are fixed at some miniscule micro scale, many features of macro scales will be fixed as well. Still, it is likely not the case that we can derive the macro features from the micro ones. This seems to me to be reason enough to deny that the special sciences are reducible to more fundamental sciences as well as that objects of the special sciences are reducible to arrangements of fundamental particles or fields. However, if someone wants to argue that this epistemic point is completely separate from

[2] For instance, that the walls of the container are perfectly elastic.

any metaphysical question of reduction and that this sort of supervenience amounts to reduction, then our dispute will be merely a terminological one.

Another tenet of my brand of naturalism is the acceptance of a non-Positivist version of verificationism. The claim is that a metaphysical hypothesis must either be such that it is possible for empirical evidence to bear on it or such that it could be inferred from some measurement or measurements taken from some physically possible perspective. In other words, given the actual laws of nature, is there some location within spacetime that could be occupied by some sort of observer (either mind or machine) that could collect data that might bear on the metaphysical hypothesis. Further justification of this view can be found in Chapter 4.

Though I do follow a naturalistic methodology, my positive view should appeal to analytic metaphysicians as well as to naturalistic philosophers of science. The view scores well on traditional standards such as simplicity, ontological parsimony, and to some extent intuitive plausibility. I have made use of a number of notions that LRCS use in order to help introduce the metaphysical view of Ontic Structural Realism. Though I do find the view to be a compelling view, I do not discuss it here as nothing for which I argue in the dissertation depends on it.

1.3. What is a mathematical structure?

The last question that must be addressed before we proceed to more substantive metaphysical issues is the question of how we are to understand the notion of a mathematical structure. The picture I present below is borrowed heavily from Wolfgang Spohn's (2006). I make several minor adaptations to his account, and these are noted as they occur. Though the account is not fully fleshed out, I include it here merely to give readers some idea of what is meant by mathematical structure.

Spohn begins his ontological project by starting with possible objects and properties. However, we should not take this to reflect any sort of commitment to the metaphysical primacy of objects and properties over structures. We begin by taking the class D of all possible objects and class $\mathbf{P}$ of all possible n-place properties (where $n \geq 0$).

His goal is only to sketch the basic assumptions rather than the full details of the axiomatic characterization of D and **P**. These assumptions are as follows.

P must have an algebraic structure. Each class $\mathbf{P}_n$ of all n-place properties is a *Boolean* algebra and thus comprises conjunctive, disjunctive, and negative properties. Further, each $P \in \mathbf{P}_n$ has a *range of applicability* $A(P) \subseteq D^n$, the purpose of which is to avoid category mistakes[3]. Though Spohn does not give a full account of the assumptions relating properties having a different number of places, he does define the application operation α that is defined for a property $P \in \mathbf{P}_n$ and an object $d \in D$ when d is in $A(P)$ and fills the n-th place of P, thus turning p into an n-1-place property $\alpha(P, d)$.

The application of a property to an object creates a state of affairs, a new object in our ontology but does not *assert* that the property actually applies to the object. $\mathbf{P}_0$ forms the important class of all possible states of affairs. Spohn defines a class of properties as *algebraically closed* if it is closed under this vaguely sketched set of algebraic operations without the application operation α and *applicationally closed* if it is closed under α.

Spohn contends that it is just the application operation α that creates relational properties. All properties not generated at least once by the application operation α are non-relational. These include the special properties of *identity* ≡ and *actual existence* E, which are both in **P**. Though they are non-relational, they are not qualitative. Thus, Spohn postulates a class **Q** of qualitative properties or *qualities*, which is algebraically closed. **Q** does not contain identity, actual existence, or 0-place properties, as he says there are no purely qualitative states of affairs. So as to provide the option to avoid including identity and actual existence among the properties, Spohn defines the class **P*** of *proper properties* as the applicational closure of **Q**.[4]

The *actuality operator* **@** applies to states of affairs and states them to be *facts*. It must also conform to the algebraic behavior of states of affairs.

[3] Spohn does not delineate how the Boolean structure interacts with the ranges of applicability.
[4] The applicational closure of $\mathbf{Q} \cup \{\equiv, \mathbf{E}\}$ is just the class **P** of all possible properties.

The final notion Spohn introduces is that of *ontological necessity*, which is represented by an operator **N** that applies to a one-place property $P \in \mathbf{P}_1$ and an object $d \in D$ and says that P is an *essential property* of d. The conjunction of all the essential properties of d forms the *essence* of d. An object cannot exist or keep its identity without its essence; any object not having the essence of d must be different from d. "Thus, objecthood is fundamentally a modal notion" (108). Spohn introduces a further operator $\Box$ for states of affairs that asserts their ontological necessity.[5]

Spohn appeals to Leibniz's principle to justify the claim that an object cannot exist or keep its identity without its essence. What is the domain of quantification for Leibniz's principle? Spohn takes it to be limited to one-place properties. Self-identity, of course, must be excluded lest it render the principle trivial. Spohn also excludes actual existence, as he does not think it can be the only feature distinguishing two objects. This leaves us with the proper properties. Spohn also thinks it is inappropriate to characterize an object by its contingent properties, so he formulates a version of Leibniz's principle that applies only to objects' proper essential properties (note that this does not exclude relational properties). The proper Leibniz principle (L) is as follows:

(L): For all d, $d' \in D$, $d = d'$ if and only if d and d' have the same proper essence.

Thus, according to (L), the proper essence is not only necessary but also sufficient to fix an object's identity. This, of course, is incompatible with the doctrine of haecceitism. While haecceitism is by no means universally rejected, I take it to be relatively clear that it is incompatible with naturalism. A naturalist is committed, I think, to the view that there is no part of reality that is in principle hidden from view and that could thus never be discovered scientifically or inferred through our best unifying metaphysics. Thus, the

[5] While Spohn does not say much about the relationship between his system and standard modal logic, they could presumably be unified by adding **N** and @ to the algebra of properties, then defining possible worlds as maximal consistent sets of formulas and the accessibility relation in terms of the **N** operator. If an object has an essential property at the actual world, then it has it at every accessible world.

naturalist must reject any sharp divide between metaphysics and epistemology. This is in line with the version of verificationism that I accept, which states that if something is real, there must be some possible physical measurement or measurements from which its existence can be inferred (See chapter 3 for further reasons to reject differences that don't make a difference).

Spohn then moves on to an informal, meta-theoretic account of systems and structures. $S = \langle \mathbf{R}, E \rangle$ is a *system* if and only if $\mathbf{R} \subseteq \mathbf{P}$ and $E \subseteq D$ such that $\mathbf{R}$ and E are applicationally closed and the application operation α is always defined with respect to $\mathbf{R}$ and E. Let $S = \langle \mathbf{R}, E \rangle$ and $S' = \langle \mathbf{R'}, E' \rangle$ be two systems. Then f is an *isomorphism from S to S'* if and only if f is a bijection from $\mathbf{R}$ onto $\mathbf{R'}$ and from E onto E' such that algebraic operations on $\mathbf{P}$ are preserved under f and for all $P \in \mathbf{R}_0$ @ $(f(P))$. S and S' are *isomorphic* if and only if there is an isomorphism from S to S'.

Spohn characterizes structures in terms of properties that isomorphic systems share. He says that property $\mathbf{S}$ of systems is a *structure* if and only if some system S has $\mathbf{S}$ and if for any two isomorphic systems S and S' either both have or both lack the property $\mathbf{S}$. $\mathbf{K}$ is a *categorical structure* iff any two systems having the structure $\mathbf{K}$ are isomorphic. If we require that mathematical structures be categorical, then we will not have to face problems relating to inconsistent structures. The structure of the natural numbers is not categorical in first-order logic, but it is in second-order logic. The categoricity of the natural-number structure is essential for speaking of numbers as *places* in *the* natural-number structure. Contrast this with groups. There are many non-isomorphic groups, and therefore it does not make sense to speak of *the* places of *the* group structure. The group structure is not categorical. But if we fix the cardinality of a group to be a particular prime number, it is categorical.

In the end, I find Spohn's definition of a *canonical system* to be more in line with what is generally meant by structure, but we will forge ahead with his vocabulary in order to define the notion of a canonical system.

Here is the corresponding existence axiom for objects in D and properties in $\mathbf{P}$:

(M) For each categorical structure $\mathbf{K}$ there is a distinguished minimal system $S^{\mathbf{K}} = \langle \mathbf{R}^{\mathbf{K}}, E^{\mathbf{K}} \rangle$ such that

- (a) $S^{\mathbf{K}}$ has the structure $\mathbf{K}$,
- (b) for each $P \in \mathbf{R}_0^{\mathbf{K}}$, $@(P) \Leftrightarrow \Box P$,[6]
- (c) for each $P \in \mathbf{R}_0^{\mathbf{K}}$, $A(P) = (E^{\mathbf{K}})^n$
- The system $S^{\mathbf{K}}$ is called the *canonical system* having $\mathbf{K}$.

My proposal is just that we call the canonical system the *structure*. Categorical structures would be better referred to as "isomorphism classes." For each isomorphism class, there will be a distinguished minimal system and that one is the structure. Condition (b) says that the properties the canonical system has are all and only those properties that it has essentially. The minimality condition (c) means that it would be wrong to ascribe any non-structural properties (like the property of being red or the property of being non-red) to the structure or to places in it and that the properties in $\mathbf{R}^{\mathbf{K}}$ do not apply beyond the objects in the system.[7] Both of these conditions intuitively seem to be in line with what structuralists have in mind. "(M) specifies the relational essences of mathematical objects, and according to (L) this is all we have to do in order to generate these objects and fix their identity. The essences are not specified individually; rather they are specified for all objects of a canonical system at once; all of them are mutually ontologically dependent" (116). In all, (M) seems to capture the features of mathematical structures that structuralists desire.

It is worth emphasizing again that I do not take the order of definition (first objects and properties, then structures) to reflect anything about metaphysical primacy. We start with objects and properties as a way to get a grasp on the notion of structure, but we should not therefore take structures to be reducible to the objects in terms of which they are defined. I think this is also fits with the picture that Spohn intend. Spohn means

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[6] The use of a biconditional here is mine. Spohn only uses a conditional. Presumably, this is just because he intends $\Box$ and $\mathbf{N}$ to entail actuality.
[7] A consequence of this is that the natural number 2 will not be identical to the real number 2, but I do not see this as an objection.

for his version of (M) to be an unconditional existence postulate. He thus takes ontology to be independent of provability and so rejects that idea that we somehow construct mathematical structures and objects through proof. This picture is thus well-suited for a realist about mathematical structure.

2. Necessary Laws and Chemical Kinds

2.1. Introduction

Before the advent of semantic rigidity, the dominant view among philosophers was that all necessary truths are knowable a priori. Kripke shifted the philosophical consensus to the view that some necessary truths are knowable only a posteriori. Though he introduced rigid designation as part of an attempt to formulate a semantic theory of proper names, he saw the notion as extending beyond proper names to include the semantic behavior of natural-kind terms. While he did not explicitly formulate an account of what it means for natural-kind terms to be rigid, he saw their rigidity as supporting the necessity of theoretical identifications, statements such as ‘gold is an element’ and ‘water is H_2O’ that he took to be both empirically determined and necessary if true. While current consensus is that Kripke showed there to be necessary truths that are knowable only a posteriori, such truths are generally taken to be the exception rather than the rule, even when it comes to statements that involve natural-kind terms and express laws of nature. This paper challenges that assumption.

In the past decade or so, several philosophers have proposed dispositional accounts of property-individuation, which identify what a property *is*, in part, with what that property *does*. These views suggest that the nature or essence of a natural-kind property is inextricably linked to the types of behaviors that instances of the kind generally exhibit, as described by the laws of nature. Notable among them are Shoemaker’s (1998) causal theory of properties, Hawthorne’s (2001) causal structuralism, and Bird’s (2007) dispositional essentialism. These views share the consequence of making Kripkean statements of a posteriori necessity commonplace, as laws describing the behavior and interaction of natural kinds will be both metaphysically necessary[8] and discoverable only empirically. Because these views share the consequence of making Kripkean statements of a posteriori necessity commonplace, renewed interest in law necessitarianism has been associated with the rise of views like dispositional or scientific essentialism. However, one need not assume such a view of properties in order to argue that there is more a posteriori necessity around than is usually posited, and that it is frequently to be found in the laws of nature.

In his (2001), (2002), and (2005), Bird argues for the view that some higher-level laws of nature may turn out to be necessary, given a certain 'down-and-up structure' of supervenience they have on lower-level laws.[9] While he does accept dispositional essentialism, the view does not play any role in this argument. Suppose there is a higher-level law that describes the behavior of some substance and that that substance can exist only given a certain underlying law.[10] So as not to beg the question, assume that the underlying law is contingent. If the underlying law entails the truth of the higher-level law, then even if the underlying law is contingent, the higher-level law turns out to be necessary. We can see this if we realize that, in order for a world to provide a counterexample to the higher-level law, the world must be one in which the substance exists but the law fails to hold. Worlds in which the substance does not exist will be worlds at which the statement of the law is vacuously true.[11] Further, since the structure of these higher-level laws can only be discovered empirically, their necessity is an a posteriori matter. This runs counter to *contingentism,* which holds that laws of nature are

[8] This is because the nature of a property is identified with the property's causal profile or disposition. Thus, the property could not have produced different behaviors than the ones it leads to in the actual world.

[9] Here, a 'higher-level' law is any law that is not part of fundamental physics. Some higher-level laws will be lower-level laws *with respect to* other higher-level laws (e.g., laws governing cell division will be lower-level with respect to laws governing multicellular organisms).

[10] The use of the term 'substance' is not intended as an endorsement of any specific metaphysical account.

[11] Some may object that a statement that is vacuously true at a world does not deserve to be considered a law at that world. This can be accepted without detriment to the argument. For, even if the law is not a *law* at every world, it is still *necessary* at every world, and it is the necessity of the law rather than its lawhood that interests us here.

contingent and that their contingency is knowable a priori. As it is the received view regarding the modal status of laws of nature, it is rare to find explicit defenses of contingentism. However, Lewis (1986) and Sidelle (2002) each propose and endorse a contingentist account, and Bealer (2004) supports a version of the view.

One reason that contingentism is so widely accepted is that it is a consequence of Humeanism about laws of nature. The traditional Humean view is a conjunction of two theses, which Maudlin (2007) calls *Separability* and *Physical Statism*. Separability is the thesis that the complete physical state of the world is determined by the intrinsic physical state of each spacetime point and the spatio-temporal relations between those points. Physical statism is the thesis that all facts about a world, including modal and nomological facts, are determined by its total physical state. It entails that no two worlds can share a total physical state but differ in their laws of nature. On the Humean view, which laws of nature hold at a given world depends upon the patterns of regularity over property distributions at the world. Following Lewis, Humeans often accept a principle of recombination, which attributes metaphysical possibility to all combinations of objects and properties that are not logically inconsistent. So if the distribution of properties and objects at a world determine what laws of nature hold at that world, and any imaginable combination of objects and properties constitutes a possible world, then the laws of nature are metaphysically contingent. Thus, Humeanism has contingentism as a consequence, and if contingentism is to be rejected, so too is Humeanism.

Given that contingentism is a consequence of Humeansim about laws as well as of the principle of recombination, Bird's argument against it has wide-ranging consequences for the way we think about metaphysical modality and modal epistemology. The existence of a necessary law of nature shows that metaphysical necessity is more restricted than mere logical necessity. Thus, neither a Lewisian principle of recombination nor our unrefined pre-scientific modal intuitions can offer reliable assessments of what is metaphysically possible.[12] That the modal status of a law of nature can sometimes only be discovered a posteriori is deeply counter to the view that

[12] George Bealer expresses a view of the latter sort in (2004).

conceivability offers a guide to possibility. Such purely a priori heuristics are blind to the structural features of the world uncovered by scientific investigation. The inter-structural relations that hold among higher- and lower-level laws and between laws and substances are empirical features of the world that are key to our understanding of the modal status of its laws.

Particularly in the special sciences, it is imperative to know how higher-level laws relate to more fundamental laws if we are to determine the metaphysical status of the former. Some philosophers assume that if a law is ceteris paribus, as laws of the special sciences are often taken to be, then the law must also be contingent. But a law's being contingent upon certain conditions is not the same as the law's being *metaphysically* contingent. For if the law holds in every world in which the conditions obtain, then the law, though ceteris paribus, is metaphysically necessary. If we take some generalization to be a law in the actual world, despite its ceteris paribus nature, then we should take it to be necessary if it holds, ceteris paribus, in all possible worlds. But we cannot know whether or not it does without empirical investigation. As Bird (2002, 258) puts it, "If we discover some higher-level law experimentally but do not know what makes it hold, we will not be in a position to know whether it is necessary or not." Thus we cannot determine a priori whether ceteris paribus laws, the higher-level laws of the special sciences, are necessary or contingent.

Responses to Bird have focused primarily on attacking the example he uses to illustrate down-and-up supervenience, but they have tended to miss the point of Bird's original argument. The attacks presuppose a priori that certain scenarios are straightforwardly metaphysically possible, which is exactly the methodology that Bird's argument warns against. I defend Bird's thesis, that the ceteris paribus law that salt dissolves in water is necessary, from several misguided objections. The first objection proposes a scenario in which a disjunctive form of Coulomb's law would allow for the failure of salt to dissolve in water, and the second aims to provide a counterexample by imagining a world in which the structure of the water molecule and thus its polarity differs from its structure in the actual world. I dismantle the first by showing i) that the suggested scenario cannot act as a counterexample to the law, and ii) that there is likely no change to Coulomb's law that could allow for the scenario in the purported counterexample to occur. I respond to the second objection by attacking its problematic assumption that a molecule of H_2O could form a different structure than the one it forms in the actual world. I also defend the view against an imagined counterexample in which an additional force is posited to prevent the dissolution of salt in water. I suggest that, given the supervenience of the macro on the micro and the unified nature of the fundamental physical forces, many higher-level laws of nature are necessary. I conclude that a shift in the way philosophers think about possibility is needed.

2.2. Salt, Water, and Dissolution

Bird's argument primarily applies to those laws of nature that describe the interaction of two substances, where that interaction is explained by some further underlying law. As an example, he uses the law that salt dissolves in water. Call this law L. The argument runs as follows:

1. Necessarily, the existence of substance *s* requires the truth of underlying law C.
2. C entails L.
3. For L to be contingent, there must be a world *w* at which *s* exists and L is false.
4. Hence, L is necessarily true.

In the case of salt and water, we understand the underlying law C to be Coulomb's law, which governs electrostatic attraction.[13] For it to be contingent that L, there must be a world in which salt and water exist but C fails to hold, as L will be vacuously true in worlds in which salt or water fail to exist. As it turns out, the existence of salt and water

[13] Bird does acknowledge that Coulomb's law *alone* is not enough to determine the solubility of salt in water, but he suggests that we can take C to be the conjunction of whatever other laws are required for salt to exist (e.g. Newton's second law, laws of quantum mechanics such as the spin-statistics theorem, the Pauli Exclusion Principle, etc.) – all of which, Bird argues, will determine that salt dissolves in water.

requires, necessarily, the truth of C. So there is no world in which salt and water exist but C fails to hold, and L turns out to be necessary.

To support (1), Bird argues that Kripke and Putnam-style arguments about the essentiality of certain natural-kind properties can be extended to the structural properties of water and salt molecules. Since it is necessary that water is composed of hydrogen and oxygen and that salt is composed of sodium and chlorine, Bird thinks it follows that, necessarily, water molecules are held together by covalent bonds and salt molecules are held together by ionic bonds. It is not the case that just any *mixture* of hydrogen and oxygen atoms is water – the atoms have to be held together in a certain way. They must compose a *compound*. Similarly, it is necessary that any instance of a salt molecule is an instance of an ionically bonded sodium-chloride molecule. Bird takes the notions of *compound*, *molecule*, and *ionic bond* to be structural notions. It important to note here that since ionic bonding is electrostatic in character, it is governed by Coulomb's law. Thus, if ionic bonding must exist in order for salt to exist, and ionic bonding just is the type of bonding that exists by virtue of Coulomb's law, then Coulomb's law must obtain in any world in which salt exists.

Coulomb's law governs electrostatic attraction between bodies. Its mathematical formulation is as follows:

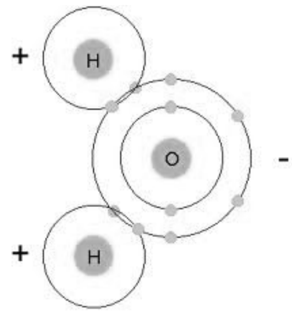
$$F = k_e (pq/r^2)$$

This says that the magnitude of electrostatic force (F) between two charged objects is directly proportional to the product of the two magnitudes of each charge (p, q) and inversely proportional to the square of the distance (r) between the charges.[14]

With the structure of Coulomb's law in mind, we can begin to understand the phenomenon of dissolution. The process of dissolution is entirely electrostatic in character. Recall the structure of the water molecule, shown at left. The hydrogen atoms are positively charged and the oxygen atom is negatively charged, making the molecule a dipole. The oxygen end of the molecule has a high polarity. This is what allows the

[14] k_e is a constant, which we can ignore for the purposes of this paper.

molecule to pull sodium ions away from the surface of the salt crystal into the surrounding liquid, causing the crystal to dissolve. The salt crystal, shown on the right, is a cubic lattice made of smaller sodium ions alternating with larger chlorine ions. The bars between the ions represent the ionic bonds holding them together.



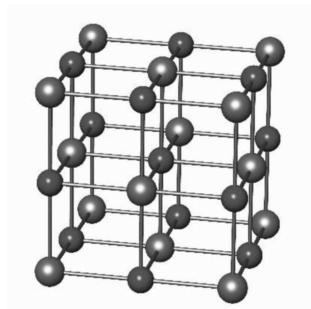


Figure 1: H_2O molecule (left)

Figure 2: NaCl molecule (right)

Since dissolution is an electrostatic process, the force that the water dipole exerts on a sodium ion on the salt crystal's surface is governed by Coulomb's law. Since that force is greater than the force exerted on that same sodium ion by its surrounding chlorine ions, the sodium ion is pulled away from the crystal's surface and into the liquid. This happens to each of the sodium ions, and the entire crystal is dissolved.

2.3. Contingentist Reply: Tweak Coulomb's Law

I now respond to an objection that I think misses the point of Bird's argument and that has not yet received an appropriate response in the literature.[15] Beebee's (2002) objection focuses on Bird's claim that the existence of salt requires or presupposes Coulomb's law (or something very much like it). Beebee first imagines a misguided objection to Bird. The imagined objection is this: Perhaps there is a world in which Coulomb's law is false but a law very like it is true, allowing for the existence of salt and

[15] Bird addresses Beebee's objection in (2002), but his response focuses on the epistemic possibility that the down-and-up structure between higher- and lower-level laws holds in other cases besides this one; if it holds in even one other case, his original argument would still stand. I take the more direct approach of showing why Beebee's scenario cannot be a counterexample to Bird.

water. She offers a response to this herself: A law that is similar enough to Coulomb's law to allow for salt and water to exist will also determine (something very like) the dissolution of salt in water.

Rather than positing a world in which something very like Coulomb's law is true, Beebee considers a world w_1 in which Coulomb's law is replaced by a disjunctive law, so that the value of F generally equals $k_e\,(pq/r^2)$[16] but occasionally – and inexplicably – equals $k_e\,(pq/r^4)$[17].[18] Beebee acknowledges that, were F to always have this value at w_1, the world would be too different from ours for salt to form at all – but she stresses that, even though Coulomb's law is false at w, there is still enough "relevant regularity" in w_1 for concepts such as *electrostatic attraction* and *ionic bonding* to be well-defined. While I do not here dispute this claim, I do not think it unproblematic. What I do wish to challenge is Beebee's characterization of the interaction between salt and water molecules at w_1:

> Suppose that, in fact, the ionic character of all lumps of salt at w_1 is exactly the same as that of actual lumps of salt. So salt at w_1 really does deserve to count as salt. But it just so happens that sometimes (or perhaps almost always), when one puts such a lump of salt into water, the electrostatic attraction exerted by the water dipoles on the sodium atoms is *not* such as to pull those atoms away from the sodium crystal and into the water. (I have no idea whether $F = k_e\,(pq/r^4)$ will turn the trick, but something will.) So sometimes – almost always, if you like – salt fails to dissolve in water. So at w_1, it is not true that salt dissolves in water. Hence, it is not metaphysically necessary that salt dissolves in water.

[16] Its actual value.
[17] She supposes that setting the value of F to $k_e\,(pq/r^4)$ will be a drastic enough departure from the actual world that the charge exerted by water molecules on sodium atoms will not be enough to pull the atoms away from the sodium crystal of which they are a part.
[18] It is worth noting that, in this world, F can no longer be considered a dimensionless constant of nature as it is in the actual world, making Beebee's envisioned world indeed quite different from our own. It is primarily this point on which Bird focuses in his (2002) response to Beebee and Psillos.

This scenario, however, fails to constitute a counterexample to L, as w_1 cannot simultaneously accommodate the existence of salt alongside the conditions required to prevent its dissolution in water. If the value of F at w_1 differs for different regions of space-time then the regions in which F does not equal $k_e\,(pq/r^2)$, the value it has at the actual world, are areas where salt will not form or exist. If $F = k_e\,(pq/r^4)$ does 'turn the trick' to make the water dipoles fail to pull the sodium atoms away from the crystal and into the water, then it will *also* preclude the formation of stable water molecules and sodium crystals in the areas of w_1 in which it obtains. It will thus still be the case in w_1 that, wherever salt and water exist, salt dissolves in water.

What seems to be required for w_1 to constitute a counterexample to L is for there to be a region of space-time in which F has the Coulomb value and in which salt is located, and for the area to border one in which F has the non-Coulomb value and in which there is water. But this is not yet sufficient.[19] In order for a molecule of salt to dissolve in water, it must be surrounded by water molecules. Let us suppose then that the area of space-time where the salt molecule is located is exactly the area of w_1 in which F has the Coulomb value. The surrounding area of w_1 is one in which F has the non-Coulomb value, and it is occupied by water molecules. Thus, we may accurately say that the salt is in the water, but the water fails to dissolve the salt. We shall assume that if this case were possible, it would constitute a counterexample to Bird. But let us consider what is required for this case to be possible.

If it is the case that the liquidity of water depends on Coulomb's law holding, then it will not be possible for water molecules to join together into a liquid body in an area in which $F= k_e\,(pq/r^4)$. In liquid water, molecules of H_2O are bonded together through hydrogen bonding, an instance of dipole-dipole attraction – the dipole moment of one H_2O molecule bonds to a hydrogen atom of another, as shown below.

[19] For, a salt molecule spatially located next to a water molecule is not a case to which we may apply to the concept *dissolves*. It is no equivocation to say that, for salt to fail to dissolve in water, salt must be *in* water.

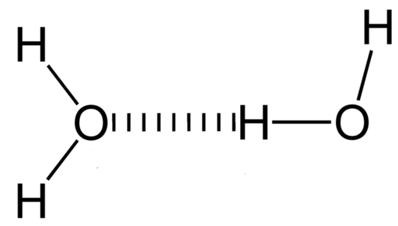


Figure 3: Two H_2O molecules are bonded together through hydrogen bonding.

Most other small compounds, such as carbon dioxide, hydrogen chloride, and hydrogen fluoride, are gaseous at room temperature. It is an anomaly that water is a liquid at room temperature, and it is hydrogen bonding that is responsible for this remarkable fact. Just as Bird showed that it is necessary that every salt molecule is held together by ionic bonds, we can see that it is necessary that every instance of liquid water is one in which H_2O molecules attach to one another through hydrogen bonding. Hydrogen bonding, being an instance of dipole-dipole attraction, is electrostatic in character, and as such, is governed by Coulomb's law (IUPAC 1997/2006). So it is not the case that there is a possible world in which liquid water can form in a region of space where *F* has a non-Coulomb value. Since both salt and liquid water must be present in a world in order for it to constitute a counterexample to L, and since the existence of both salt and liquid water require Coulomb's law to have the value that it does in the actual world (or something very much like it), we are again left without a counterexample to L.

Beebee's misstep is that she presupposes, in the setup of her counterexample, the very independence of laws that her opponent cautions against presupposing. In order for Beebee's scenario to provide a counterexample, it must be the case that water molecules in w_1 can form a liquid despite the fact that the force allowing them to do so is far different from what it is in the actual world – different enough to prevent the stable formation of salt molecules. But since the existence of liquid water requires hydrogen bonding as much as the existence of salt requires ionic bonding, and both are governed by Coulomb's law, Bird's opponent cannot assume that the existence of liquid water at a world can be stipulated independently of the value of *F*. It is ironic that, in Beebee's attempt to construct a counterexample to Bird, her failure to consider liquid water's underlying structure serves as a perfect illustration of the fact that Bird's down-and-up structure is more ubiquitous than philosophers tend to assume.

Clearly, it is not the case that a disjunctive form of Coulomb's law can offer a counterexample to L. But there is another, more deeply rooted problem with Beebee's scenario that has also gone unmentioned in this debate. Her conviction that, in some possible world, the value of Coulomb's law will be both sufficiently similar to its actual value to allow salt to exist and sufficiently different from its actual value to prevent salt from dissolving in water demonstrates a misunderstanding of the nature of Coulomb's law. Coulomb's law is a relational value – a ratio of the product of the magnitudes of two charges to the square of the distance between them. Consider again the English interpretation of $F = k_e\ (pq/r^2)$: "The magnitude of the electrostatic force between two point-like charged objects is directly proportional to the product of the magnitudes of each charge and inversely proportional to the square of the distances between the charges." We can see that p and q represent the magnitude of each charge and r the distance between the two charged objects. In order for salt not to dissolve in water, it would have to be the case that the value of F_1, where p and q are the charges of the sodium ions and the chlorine atoms in the salt crystal and r the distance between them, is greater than the value of F_2, where p and q are the charges of the sodium ions and the water dipoles and r the distance between them. While changing the Coulomb equation will change the numerical values of F_1 and F_2, it will not change the relation of F_1 to F_2 from *less-than* to *greater-than*. And it is exactly this change of relation that is required for salt's failure to dissolve in water. Not only will $F = k_e\ (pq/r^4)$ not 'turn the trick' – nothing will.[20]

Beebee assumes that there could be a value of Coulomb's law that would leave untouched the strength of the ionic bonds holding the salt crystal together while weakening the electrostatic attraction exerted by the water dipoles on the sodium ions. She mistakenly conceives of the electrostatic attraction of the salt crystal's ionic bonds as

[20] Of course, taking the reciprocal of (pq/r^4) would change the relation of F_1 to F_2 from *less-than* to *greater-than*. But this would seem to be just the sort of change to Coulomb's Law that Beebee would take to be too drastic to allow salt or water to exist.

a separate phenomenon from the electrostatic attraction between the water dipoles and the sodium ions. They are not, however, different in kind such that the strength of one can be manipulated independently of that of the other. They are both instances of electrostatic attraction (indeed, both of electrostatic attraction involving sodium ions), and as such, they will rise and fall together with any change to Coulomb's law.

2.4. Contingentist Reply: Change the Structure of the Water Molecule

Psillos's (2002) objection attempts to put pressure on the claim that any world in which salt fails to dissolve in water is a world in which Coulomb's law is false. Psillos imagines a world w_2 in which Coulomb's law holds but H_2O, having a linear rather than a bent structure, fails to dissolve salt. Psillos asserts that instances of H_2O in w_2 would still be instances of water, and Bird (2002, 264) agrees. Let us concede, for the sake of argument, that if such a world were possible, it would constitute a counterexample to Bird. I show, however, that it is not the case that there could be a molecule of H_2O with a linear structure, and thus, that Psillos's imagined world is not a possible world.

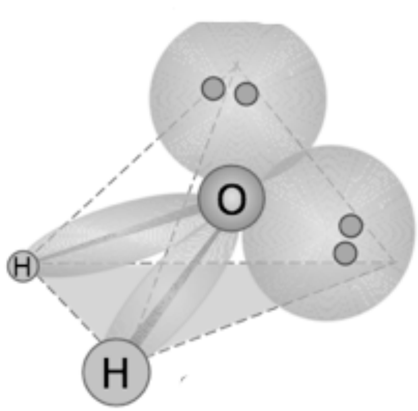
Consider the following fact of chemistry: Every chemical compound has two formulae that must be expressed in order to identify it (and individuate it from others). These formulae are:

1. <u>Chemical/molecular formula</u> – Identifies each constituent element of the compound by its chemical symbol and indicates the number of atoms of each element found in a discrete molecule of that compound (e.g., water's chemical formula is H_2O)
2. <u>Structural formula</u> – A geometric graphical representation of the molecular structure of a compound, which shows how the molecule's atoms are arranged and how its elements are chemically bonded to one another.

There are six basic types of molecule structures, out of which all others are built: linear, trigonal planar, tetrahedral, octahedral, pyramidal, and bent. As I mentioned earlier the

H_2O-molecule has a bent structure, and is always bent at an angle of 104.5-degrees.[21] If it were the case that a given molecule's structure were some primitive, brute property, not determined by nor derivable from the underlying features of the molecule's components, then Psillos's scenario might not be so problematic. But, I argue, this is not the case.

Certain facts about charge, repulsion, and equilibrium cement the inevitability of the H_2O-molecule's 104.5-degree angle. The above mention of a molecule's structural formula touched solely upon the notion of molecular geometry, but each molecule also has a coordination geometry. While molecular geometry describes only the angles that form between the molecule's atoms, coordination geometry additionally includes the angles that form among the molecule's electron pairs. Consider the figures below, which show both the



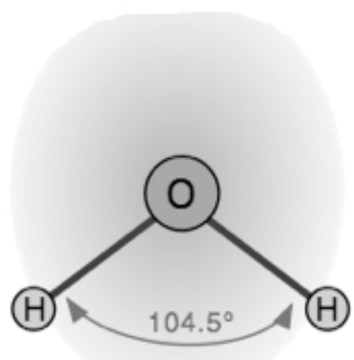


Figure 4: Tetrahedral coordination geometry of the H_2O molecule (left)

Figure 5: H_2O's Molecular geometry (right)

coordination and molecular geometry of the water molecule.

A molecule's molecular geometry is derivative upon its coordination geometry.

[21] The H_2O molecule is always bent at the 104.5-degree angle. What I mean by this is that the *equilibrium* angle of the H_2O molecule is always 104.5 degrees. I do not mean to suggest that it is never the case that an actual H_2O molecule is found bent at a slightly different angle. Rather, it is never the case that H_2O has some other equilibrium angle. This is, of course, meant to be compatible with facts about molecular vibration (*i.e.* the internal movement of atoms in a molecule).

Coordination geometry refers to the shape made by a molecule's distribution of electron pairs around its central atom. The H_2O molecule has two bonded electron pairs, each located at one of the molecule's two hydrogen atoms, and two lone unbonded pairs (McQuarrie and Simon 1997, 379). The lone pairs have a negative polar character and are located closer to the central atomic nucleus (the oxygen nucleus). Because of the repulsive force of the lone pairs, the hydrogen atoms are pushed farther away from the central nucleus, to the point where the forces of the electrons on the hydrogen atoms are in equilibrium. At the point of equilibrium, the molecule has tetrahedral coordination geometry, as shown in the figure on the left. In every case, the angles composed by the coordinates [H, H, lone-pair] are 109.5 degrees, and the inner angle [H, O, H] is 104.5 degrees. Thus, whether the geometry of a molecule is linear or bent (at a particular angle) depends on which structure is lowest in energy (1997, 384).

The important point is that the H_2O molecule has tetrahedral coordination geometry because that is the structure in which all of its forces are in equilibrium. If one were to attempt to change the structure of the H_2O molecule across possible worlds, one would first have to change the underlying laws regarding charge, repulsion, and equilibrium. Changes of the sort required would be so drastic that it is not at all clear that the resulting worlds would be ones in which our scientific concepts *element* and *molecule* would have extensions. It is doubtful even that such changes would be possible. Recall the role that electron repulsion plays in creating a stable molecular structure. The fact that electrons repel one another results from their having the same charge. It is uncontroversial that fundamental particles of the same kind cannot differ from one another in their intrinsic properties, such as charge. Thus, it does not look like we can construct a possible world in which H_2O has a different structure without radically altering essential properties of the fundamental particles. Once we know that molecular structure is determined in part by an essential property of electrons, it is much more difficult to imagine a possible world in which only the structural properties of the H_2O molecule differ from the actual world while the underlying laws are left untouched.

2.5. Contingentist Reply: Posit an External Force

A tempting response for the contingentist is to allege that not all potential counterexamples to L have been considered. Could there not be a world w_3 in which Coulomb's Law is left untouched, but some additional exotic force prevents salt from dissolving in water? We might posit a force that only acts when an NaCl molecule comes in contact with water, overriding the electronegative pull of the water dipole on the surface ions of the salt crystal and preventing dissolution. That Coulomb's Law remains the same in w_3 allows for the existence of the relevant substances, while the extra force ensures that whenever salt comes in contact with water it fails to dissolve. I contend that upon deeper investigation, it becomes clear that such a force could not exist in a world suitably close to our own to contain salt and water.

It is widely accepted among metaphysicians and philosophers of science that the macrophysical states of the world supervene on the more microphysical states. While this view is not undisputed – its opponents include Nancy Cartwright, whose (1983) suggests that science is inherently disunified, and Jonathan Schaffer, whose priority monism inverts the traditional direction of dependence between macro to micro – it is fair to say that opponents of this view constitute an extremely small minority.[22] Whether or not one accepts a version of reductionism, most can agree that there is an important sense in which the state of the macroscopic world metaphysically depends on the state of the microscopic world. For our purposes, the relevant supervenience is that of the chemical on the physical.

With this hierarchy of sciences in mind, it should be easier to see why the force in w_3 is not one that could arise given the supervenience of the chemical on the microphysical. Consider what features the imagined force must have in order to provide a counterexample to L. It must overpower or nullify electrostatic attraction *only* between water dipoles and sodium ions. It cannot exercise its power in every instance of

[22] Even Schaffer (2007) admits that priority monism has "virtually no advocates." Regardless of how widely accepted the supervenience thesis is, I assume it here and argue that it is incompatible with the additional force.

electrostatic attraction lest it prevent the formation of the ionic bonds that are necessary for a salt crystal to develop. The force must somehow discriminate between electrostatic attraction that takes place between sodium and chlorine ions and electrostatic attraction between sodium ions and water dipoles. Is this the sort of thing that a possible physical or chemical force could do?

There is strong reason to think the answer is no. First, the force would have to act at the microphysical scale of atoms in order to affect electrostatic attraction, yet also be ‘upward-looking’ enough to know in what kind of chemical or molecular structure the atoms taking part in a given instance of electrostatic attraction were to be found. Thus, whether or not the force acted at the microphysical scale on any given instance of electrostatic attraction would be dependent on chemical conditions at the macroscopic scale. If the instance of electrostatic attraction were between a water dipole and a sodium ion, the force would act; if it were between a sodium ion and a chlorine ion, it would not. Such a force would make what happens at the microphysical scale dependent on what happens at the macro-chemical scale without any underlying physical correspondence between the macro and the micro. Of course, we can think of many ways in which change at a micro scale might be dependent on a macroscopic event. Whether someone burns their cutaneous tissue (a micro event) might depend on whether they are lying in the hot sun (a macro event). But here there is a corresponding microphysical explanation of the event that occurs at the macro scale. When one is lying in the sun, UVB photons are directly absorbed by the DNA, which then becomes damaged. Direct DNA damage can be understood as the formation of mutagenic thymine dimers, which are the molecular lesions that cause sunburn and melanoma. In simpler terms, the macro event of sun burning skin can be understood in terms of microscopic photochemical reactions. While there is a difference at the macro scale between the events of merely lying in the sun and burning while lying in the sun, and there is also a corresponding difference between these events at the micro scale. In the w_3 case we are imagining, the force affects something at the macroscopic scale of chemical reaction without any corresponding change at the microphysical scale.

Suppose then that we simply adjust the scenario to include such a change at the scale of the microphysical. Since the fact that salt dissolves in water is determined by the respective chemical make-ups of salt and water molecules as well as by the nature of electrostatic attraction, the force would have to affect one of these two things in order to achieve the desired outcome of systematically preventing salt's dissolution in water. However, neither of these is a viable candidate for change. As noted earlier, it is a necessary feature of the water molecule that it is made up of two hydrogen atoms and one oxygen atom. It is a similarly necessary feature of salt that the chemical elements it comprises are sodium and chlorine. So the force could not affect the chemical make-up of either salt or water without eliminating the substances from existence. But neither can the force change the character of electrostatic attraction. Coulomb's Law is what governs the nature of electrostatic attraction, and we have already established that Coulomb's Law must be very close to what it is in the actual world in order for salt and liquid water to exist at w_3. We have further established that no change to Coulomb's Law could affect the pull exerted by the water dipole on the sodium ions while leaving the strength of the salt crystal's ionic bonds untouched. To suggest that a force could affect only those instances of electrostatic attraction that occurred between a water dipole and sodium ion is to make a mistake of the sort that Beebee does.

It now seems clear that the sort of force suggested could not exist given the supervenience of the chemical on the physical. Given the supervenience of the macro on the micro, we cannot change something at a macro scale without changing something at the micro scale. There are two possible things we can change at the micro scale, and neither change will achieve the result that the contingentist desires.

Scholars used to think that chemistry and the existence of chemical reactions challenged a mechanistic picture of the world. It was thought that forces such as chemical bonding could not be explained in terms of underlying physical forces and thus posed a threat to the Newtonian worldview. Now we know that all chemical forces have some grounding in underlying physical law. Indeed we know that all the forces in our universe are results of the four fundamental interactions: strong interaction, weak interaction, electromagnetism, and gravitation. Even these are not thought to be primitive. Electromagnetism and the weak interaction have been shown to be different manifestations of the same force, the electroweak force, which behaves as two distinct forces at ordinary low temperatures. The history of physics is one of unification, and inquiries concerning a potential Theory of Everything offer hope that all of these forces will eventually prove to be consequences of a single fundamental force or equation.

Since the existence of familiar substances necessarily requires these forces and the laws governing them to be as they are (since they are responsible for the existence of electrons, atoms, etc.), any additional postulated force must be somehow integrated into this picture. This is harder than it sounds. Though we have not yet discovered the theory of everything, physicists have unified most of the fundamental forces (all except gravitation) within a collection of symmetry groups known as the Standard Model. The structure of the combined group accurately predicts the possible particles and interactions that can exist in our world. Thus, in order to claim that our imagined force is possible, the contingentist must provide an account of how it emerges either from the group structure of the Standard Model or the interactions of forces already in existence.

I strongly doubt this can be done. If such a force were possible given the group structure of the fundamental interactions, it would likely already exist. This structure constrains the possible forces and particles that can exist alongside the ones we actually have in our universe. If a unified theory of these actual particles and forces allows for the existence of some additional force, physicists expect to observe the force in some physical circumstance. Unified theories predict the existence of particles and forces, and if these predictions are not confirmed by observation, the theory is thrown out. If the structure of fundamental forces is compatible with the existence of an additional force, we expect that force to actually exist.

2.6. Concluding Remarks

Many in contemporary analytic philosophy seem to endorse the view that everything is possible until proven otherwise. Naturally, this extends to imagined counterexamples to the laws of nature. This promiscuous view of possibility is especially likely to lead to contingentism when combined with what seems to be the default conception of a law of nature. It is common within analytic metaphysics to unreflectively assume a substantive and contentious view of laws – namely, that laws are primarily linguistic entities that can be thought of as "sentences in the book of the world." As such, they can be mixed and matched across possible worlds in any combination that is superficially coherent. This understanding of laws, which is rooted in Humean conceptions of lawhood and necessity, is a naïve one, and there are many reasons to reject it. The notion that laws are discreta that can be manipulated wholly independently across possible worlds is not one that contemporary science vindicates.

Perhaps philosophers ought to take a cue from the way scientists tend to think about possibility. In philosophy, the burden of proof is on the denier of possibility. In science, however, claims of possibility must be backed up with models. The burden is on the asserter of possibility to offer a consistent model of the allegedly possible scenario.

Rather than taking the top-down approach to modality that comes from a mix-and-match view laws, perhaps we ought to think about modal constraints as being built from the ground up on a foundation of inherently unified physical forces. Fundamental physical laws set the stage for nomological possibility in a certain sphere of worlds, and what is possible at more macroscopic spatio-temporal scales is determined by fundamental physical laws – even if they themselves are contingent. Indeed, this approach seems to fit better than its alternative with the hierarchy of the sciences and the supervenience of the macroworld on the microphysical. The chemical substances with which we are familiar will only be found in the sphere of worlds governed by our fundamental physical laws. As the natures of chemical kinds are determined in part by their bonding structures, and these bonding structures are made possible by underlying physical laws, then any world in which these chemical kinds exist will have to have physical laws quite similar to our own. When we combine this fact with the understanding that the macro-chemical supervenes on the microphysical, we should not be surprised that laws governing chemical interactions should turn out to be metaphysically necessary.

We have good reason to believe that there is far greater interdependence among chemical and physical laws than philosophers frequently assume, and the nature of this interdependence can only be discovered through empirical investigation. When evaluating the modal status of the laws of nature, one cannot ignore the relations among them that scientific investigation reveals. Many forces are at play in determining the structures and behaviors of molecular compounds, and philosophical questions about the nature of the laws describing them cannot be answered without proper consideration of these facts.

Philosophical investigation stands to gain much insight from a scientific understanding of the relations that laws, substances, and structural properties bear to one another. One outcome of this interdependence is that some higher-level laws governing the interaction of chemical kinds turn out to be necessary, as the higher-level laws are determined by lower-level physical ones, and the existence of the substances they govern presuppose these fundamental physical laws. Given the supervenience of the macro on the micro, we ought to expect the necessity of special-science laws to be the rule rather than the exception.

3. Against Sophisticated Humeanism

3.1. Introduction

The world is *prima facie* a modal place. Physical systems have modal properties, and laws of nature seem to carry the force of nomological necessity. Many of our best scientific theories make claims or describe structures that are best interpreted modally. Some examples of current scientific theories that place prohibitions on physically possible phenomena are stated below:

1) Special Relativity tells us that massive bodies *cannot* go faster than the speed of light.
2) The first law of Thermodynamics says that matter *cannot* be created or destroyed.
3) The Heisenberg Uncertainty principle tells us that a particle *cannot* simultaneously have a definite location and a definite momentum.

If we are committed to the content of our best scientific theories, we must take seriously the claim that the physical world is inherently a modal place. We must posit an objective physical modality in order to understand such things as laws of nature, causation, equilibria, and probability. These modal notions are necessary to make sense of our best scientific theories.

But how exactly are we to understand the modal properties of the physical world? Must we be committed to such a thing as natural necessity, or can we, as Menzies (1993, 201) puts it, "fashion modal facts from the thin actualistic resources of Humean empiricism?" I argue that we cannot, and that we must therefore be committed to a robust notion of natural necessity in order make sense of the content of scientific theories. In particular, I address the version of Humean regularity theory known as the best systems account of lawhood, and I show it to be plagued by three central problems, each of which make it difficult to reconcile with the spirit of scientific realism.[23]

3.2. Against Humeanism

Humeanism about causation is the denial that there is such a thing as causal or nomological necessity. Put another way, it is the view that there are no (non-logical) necessary connections to be found in nature. For the Humean, laws of nature are just a species of regularity. Of course, not all regularities are laws of nature. Some regularities are merely accidental patterns of correlation. Contrast, for instance, the true statement that, "All the coins in the cash register are quarters," with the statement that, "Every planet's orbit is an ellipse." Both statements describe regularities in nature, but only the latter expresses a law of nature. So statements of laws of nature are not just statements of regularities – they have some additional property, what is usually called the property of *lawlikeness.* It is this property that enables statements of laws to support counterfactual conditionals and to figure in scientific explanations. The Humean challenge is to identify the property of lawlikeness, which distinguishes laws of nature from accidental regularities, without appealing to a notion of physical or causal necessity.

The most widely supported version of Humeanism, often called the Mill-Ramsey-Lewis view, is the view that laws of nature are just those regularities that feature as axioms or theorems in the best axiomatic deductive system that describes our universe. It has been defended by Lewis (1973), (1983), (1986), (1994) and Ramsey (1978), as well as Earman (1984), Loewer (1996), Psillos (2003), and Cohen and Callender (2009). This so-called "sophisticated" Humeanism is supposed to avoid the problems faced by earlier versions, such as the naïve regularity view and epistemic accounts of laws. I argue that sophisticated Humeanism faces three major problems: one of its central concepts cannot

[23] While there are many different characterizations of scientific realism, for the purpose of this paper, we will take it to be the view that the aim of science is something more than mere empirical adequacy and that the best explanation of the success of science is that our theories correctly describe the unobservable causes of the observable world.

be formulated non-circularly, it can provide only an unsatisfactory account of laws in the special sciences, and it can offer no justification for inductive inference.

3.2.1 The naïve regularity view and epistemic accounts of laws

The first Humean account of laws was the naïve regularity view, which simply equated laws with universal regularities. On this view, a lawlike statement is any true universally quantified statement of the form "All *F*s are *G*s." As it denies that universal regularities must have some additional property in order to be laws, the view cannot distinguish laws from accidental regularities. This view was part of the early logical empiricist tradition and is now nearly universally rejected.

An early version of Humeanism that does countenance the distinction between laws and accidents is the epistemic view, which characterizes the property of lawlikeness in terms of our particular epistemic attitude toward those statements that we take to be laws. Strawson (1952), Ayer (1956), and Goodman (1983) have defended some version of the view. On this view, laws are those generalizations that play a certain epistemic role. "They are believed to be true, and they are so believed because they are confirmed by their instances, and they are used in proper inductive reasoning" (Psillos 2003, 141). One problem for this view is that some laws lack any positive instances. Newton's first law, for example, concerns the motion of bodies on which no forces are exerted. Since no such bodies exist, Newton's first law cannot be a law in virtue of its confirming instances.

Another disadvantage of the epistemic view is that it can offer no explanation of *why* certain generalizations should feature in proper inductive reasoning. Since the view defines lawlike regularities in part by the role they play in induction, little in the way of explanation can be offered for why some regularities rather than others play such a role. Because the lawlikeness of a regularity depends on the epistemic attitude we hold toward it, the view has also been criticized for the seemingly subjective and contingent nature of this criterion. It seems that we could have had different epistemic attitudes than we actually do toward any number of generalizations. Indeed, our epistemic attitude toward a specific generalization may change over time. The epistemic view has the consequence that the laws of nature change with our epistemic attitudes. This seems to deeply conflict with many of the motivations that initially pushed us away from the naïve regularity view – that laws are objective, unchanging, and importantly distinct from accidental regularities.

3.2.2 The objective Humean account

The Mill-Ramsey-Lewis view, or as Stathis Psillos calls it, the *web-of-laws* view, is by far the most widely accepted version of Humeanism. It offers an objective characterization of lawlikeness, and so avoids the subjectivity of the epistemic view. On this view, laws of nature are those regularities that feature as axioms or theorems in the best axiomatic deductive system that describes our world. If there is one such system that can be said to offer a true description of our world, then there are many such systems. To avoid the problem of arbitrariness, Ramsey (1990) and Lewis (2004) both suggest that the best deductive system should be the one that strikes the best balance between simplicity and strength. For Lewis, if two or more systems tie in terms of simplicity and strength, the laws of nature are to be identified with the regularities that are common to all systems. Psillos states the thesis as follows:

> (W): It is a law that all *F*s are *G*s iff (i) all *F*s are *G*s, and (ii) that all *F*s are *G*s is an axiom or theorem in the best deductive system ϕ (or if there is no unique best deductive system ϕ, it is an axiom or theorem in all deductive systems that tie in terms of simplicity and strength).

If there are no regularities common to all such systems, then the laws of nature are indeterminate. Apart from this problem of potential indeterminacy, the view is flawed in three significant ways: its notion of strength cannot be formulated non-circularly,[24] it can offer no explanation of the success of inductive inference, and it is not clear that it is compatible with a satisfactory account of the laws of the special sciences.

3.2.2.1 The circularity objection

On the web-of-laws view, we look to the best deductive axiomatized descriptions of our world to tell us which regularities count as laws of nature, and it is the theoretical virtues of simplicity and strength that tell us what those systems are. Formulating a definition of a system's simplicity is not without its difficulties, but it is the problematic notion of strength that we focus on here. Intuitively, strength has something to do with how much information can be derived from the axioms. One could say that every increase in the amount of information that is derivable from a system counts as an increase in that system's strength. This will not do, however, as any attempt to precisify such a notion seems to lead to incommensurability among systems.

Let us consider ways to explicate the intuitive notion that a system's strength is related to the amount of information derivable from its axioms. A first pass would be to formulate strength in terms of the number of facts that are derivable from a system's axioms, but this is clearly unsatisfactory. Since every system will make infinitely many facts derivable, all systems will turn out to be equally strong. Another possibility is to invoke the subset relation in the definition of strength. We could say that system A is stronger than system B iff the set of facts derivable from B form a proper subset of the set of facts derivable from A. But this notion of strength makes systems incommensurable with one another, as there will be many pairs of systems such that no subset relation holds between their respective sets of derivable facts. Is there a way to cash out the notion of strength that does not make systems either trivially equal or incommensurable in strength?

[24] While a number of authors have concerned themselves with problems for the MRL account stemming from the notions of simplicity and strength, I am aware of none that have specifically addressed this problem of circularity. See, for instance, Cohen and Callender's "A Better Best System Account of Lawhood."

Psillos's alternative approach (though he does not state this explicitly) ties a system's strength to how well it vindicates our intuitions about what statements count as laws. While this strategy escapes the problems associated with formalizing the notion of strength, it is not without its own methodological difficulties. Psillos wants to exclude increases in a system's extraneous information (i.e. information about accidents and coincidences) from counting as increases in the system's strength. But if this is to be a viable method, there must be some principled way to distinguish between the derivable information that bears on a system's strength and the information that does not. Call this the *principle of informational relevance*. The web-of-laws proponent must be able to identify such a principle if he wishes to employ strength as a determining feature of the best axiomatic system. Since strength determines (in part) which deductive system is the best one, and that in turn determines which regularities are laws of nature, the definition of strength cannot invoke the distinction between accidental and lawlike regularities, as that is the very distinction it is in the service of explaining.

I argue that no principle of informational relevance, and *eo ipso* no tenable definition of strength, can be formulated without presupposing an established fact of the matter about which regularities are laws of nature. Consider Reichenbach's statement that there are no gold chunks that are larger than a cubic mile. Contrast it with the statement that there are no chunks of plutonium that are larger than a cubic mile. Psillos takes it as a datum that the latter but not the former expresses a law of nature.[25] Thus, the latter but not the former should be derivable from the best deductive system. If we are choosing between two (sets of) deductive systems that are the same except that one includes the former regularity as an additional axiom, clearly we should choose the system without the additional axiom. How can the web-of-laws view justify this choice? The latter system ranks higher in simplicity, but can we not also say that the former rates higher in strength? After all, the former system enables us to derive a regularity that we are not

[25] It is perhaps worth noting that, in his explanation of why this is the case, Psillos appeals to the notion of physical impossibility. This is circular for the Humean, since he explicates the notion of physical impossibility in terms of what is incompatible with the laws.

able to derive from the latter – that all gold cubes are smaller than a cubic mile. One wants to justify the choice by saying that the more complicated system is *not* stronger, but in order to do this a principle of informational relevance is required.

To further illustrate the problem, consider the following passage in which Psillos asserts that the system with the additional axiom is not stronger but offers nothing in the way of explanation:

> One could, of course, just add all the accidental generalizations as extra axioms to the best deductive system of the world. But in doing this, one would make this system far more complicated than it should be. If, for instance, we were to add to the best system Reichenbach's regularity that all gold cubes are smaller than one cubic mile, we would detract from its simplicity without gaining in strength. (151)

Why wouldn't the resulting system be one that has gained in strength despite losing in simplicity? The only plausible reason is that the additional regularity we derive from the amended system is not a *law*. This response exposes the circularity inherent in Psillos's approach to explicating the notion of strength in the web-of-laws account. On this view, laws are supposed to be just those regularities that are derivable from all true deductive systems that strike a balance between simplicity and strength. But either systems are trivially equal or incommensurable in their strength, or there must already be a fact of the matter about exactly which regularities are laws and which are accidents, in order for there to be a fact of the matter about which system is stronger. Since no unproblematic notion of strength can be defined, the view's criterion of lawlikeness does not get off the ground.

3.2.2.2. Laws in the special sciences

Apart from its problem of circularity, the web-of-laws approach faces a lack of genuine naturalistic motivation.[26] It is not clear that we have any good reason to believe that all or even most of what we now take to be laws of nature would be the sorts of things that would find a place in a deductive axiomatic description of the world. Psillos seems to think the web-of-laws view is right in line with the practice of science, though he gives no explanation for this. He claims, “The useful fiction of an ideal deductive system of the world is not very far from the practice of science as we know it, nor far from what we now take the laws of nature to be.” I am not so convinced.

It may be true that attempts at unification within fundamental physics can be described as attempts to unify physics within a deductive axiomatic framework. Contemporary particle physics has been unified (for the most part) within the mathematical framework of the Standard Model, which is fundamentally a collection of symmetry groups. Mathematical systems count as deductive axiomatic systems, and so the web-of-laws view is *prima facie* compatible with the way fundamental physics is done. However, it is not as clear that this view can extend to the laws and practices of the special sciences.

It seems that the web-of-laws view requires all non-fundamental laws of nature to be derivable from the fundamental ones and implies that all the fundamental laws will be laws of physics. One of Psillos’s footnotes supports this interpretation. He finds it worth noting that, “Carnap also took the laws of nature to be whatever lawlike statements are *deducible* from a set of axioms that express a certain physical theory, or more generally, ‘the deductive system of physics’” (303). This suggests that the web-of-laws adherent expects all laws of nature that are not themselves fundamental to be derivable from an axiomatized physics.

The difficulty with this approach is that the program of reducing special sciences to physics has often been attempted though never clearly achieved. We have little positive reason to believe that the laws of special sciences are derivable from

[26] I assume a version of methodological naturalism that requires any metaphysical view to be compatible with the lessons and practices of our best science.

fundamental physics, and we do have reason to believe that such derivations are computationally intractable. I accept Ladyman and Ross's (2007) view that the laws of the special sciences allow us to make relatively accurate predictions about macroscopic systems in the world without calculating what is happening within such systems at the minute scale of particle physics. Deriving predictions about macroscopic systems from calculations made at the scale of particle physics would require far more energy than there is in the known universe. By sacrificing some level of exactness, special-science laws allow us to make predictions that would be otherwise intractable if computed using only the fundamental laws of physics.

Consider an analogy to the famous cellular automaton, Conway's Game of Life. The "game" is played on an infinite grid in which each cell can have one of two values, black or white. As in any cellular automaton, time is discrete and there are a finite number of deterministic update rules. Given any initial conditions – any starting distribution of black and white cells – the four update rules determine exactly what the grid will look like at every later point in time. Something that has fascinated Game of Life enthusiasts is the 'emergence' of macroscopic objects and patterns that seem to follow laws of their own. These higher-level laws quantify over certain types of cell configurations that behave in orderly, uniform ways. What is particularly interesting is that the derivation of many of these macro laws of the Life universe from the four underlying update rules is not a computationally tractable problem. These higher-level laws thus allow the user to make calculations about the future states of the macroscopic patterns in the Life universe by vastly compressing the relevant data.[27] It is my view that special-science laws, like the higher-level laws of the Life universe, can be understood as tools of data-compression. A more detailed account of this view can be found in "Rainforest Realism and the Unity of Science" (Ladyman and Ross 2007).

The important point is that, on this view, it is characteristic of special-science laws that their derivation from the underlying laws of physics requires carrying out unmanageably large computations. Even if some of what we now to take to be the laws of

[27] For a greater discussion of the Life universe, see Daniel Dennett's "Real Patterns."

the special sciences are, in the strict logical sense, derivable as theorems from the axioms of fundamental physics, we can never know which ones these are. Thus, if the MRL view requires all non-fundamental laws to be deducible from the axioms of physics, the view has the consequence that we cannot know which purported special-science laws are genuine laws of nature – if indeed any are. While some philosophers may accept such a view, I do not consider it to be a viable option. Like physics, the special sciences aim and succeed at discovering laws of nature, and any naturalistically acceptable view of laws must respect their ability to do so.

There are two other ways that the web-of-laws theorist could try to accommodate special-science laws, though it is unclear whether either course can offer a viable account. One strategy would be to add each non-deducible special-science law to the system as an axiom. However, this choice leads back to the circularity problem, as the web-of-laws theorist has no independent way to judge which non-deducible regularities should be counted as special-science laws, as opposed to accidents. It may also be worth noting that the notion of strength gets even murkier with respect to the special sciences, since we often cannot make straightforward derivations from special-science laws.

The other possibility would be to have separate axiomatic systems for each special science. The problem with this is that it is unclear how this version of the MRL view could represent the unity of science, *i.e.* both the hierarchical relationships among the special sciences and the relationship that the special sciences bear to fundamental physics. The criterion that special-science laws be theorems derivable from the axioms of fundamental physics is at least able to capture a sense in which physics is fundamental, though I think it is too strong a sense. At the other end of the spectrum is the view that each science has its own disparate axiomatic system of laws. This picture is unable to reflect the fundamentality of physics at all; it seems best coupled with Cartwright's (1983) and Dupre's (1993) views that science is essentially disunified. The proper account of laws in the special sciences ought to steer between these two extremes; it must reflect the unique relation that holds between fundamental physics and the special sciences without requiring anything so drastic as the reduction of the special sciences to physics.

3.2.2.3 Inductive inference

A third major problem for the MRL view is that it cannot explain the success of inductive inference. Recall that the Humean is committed to the claim that the only restriction on possibility is logical consistency. This means that the Humean must accept that there are infinitely many worlds that look exactly like ours up to a given point and then diverge dramatically. Consider, for instance, a world in which all the regularities hold that have held so far in our world, but only until January 1, 2085. On that date, negatively charged objects stop attracting positively charged ones, salt ceases to dissolve in water, and fish fail to suffocate on land. The Humean cannot deny that this world is possible else she commit herself to some necessary connection between, *e.g*, negative charge and the capacity to attract positively charged things. If this world is possible, infinitely many such worlds that follow exactly the same course as our own for a time and then diverge are also possible. Not only are they possible, they are far more numerous than worlds in which the observed regularities are eternal. The internal observers of these divergent worlds believe, just as we do, that the regularities they have observed in the past will continue to hold in the future. But they will be wrong. The problem for the Humean is that once she is committed to the possibility of divergent worlds, she can have no reason to believe that ours is not such a world.

The difficulty that these worlds create for induction is as follows. The problem of induction is the problem of justifying the belief that the future will be like the past. It seems that we are justified in believing that the sun will rise tomorrow, that electrons will continue to repel one another next year, and that a thousand years from now it will still be the case that nothing travels faster than the speed of light. But if it is possible for a world to act just the way ours does up to some future time when its electrons will fail to repel one another, then we can have no reason to believe that our world is not one such world, and so we can have no reason to believe that electrons will always repel one another.

It is true that an external observer looking at the entire distribution of properties throughout our spacetime *would* be able to tell whether or not our world is one in which electrons always repel one another. But the problem of induction is not a problem for external observers looking at the totality of facts about a world. It is inherently a problem for observers who lack full epistemic access to the future.

One might object that *after* January 1, 2085, when electrons continue to repel one another, we can know that we are not in a divergent world where the electron-regularity stops holding on that date. Certainly this is true, but it in no way provides a satisfactory response to the problem. For there will be an infinite number of possible worlds that are identical to ours up until to some point of divergence, for every possible point of divergence, that is, for every moment in time. Some worlds will have all the same regularities that we have observed in our own up until the moments just before they end. While we can eliminate infinitely many epistemic possibilities for every point we pass in time, there will always be infinitely many more that we cannot eliminate.

The MRL account of laws is of no use in providing a Humean response to the problem of induction. Consider the only approach that the view could take in order to explain how our inductive inferences are justified. The MRL view would appeal to the fact that a given regularity is an axiom or theorem in the best deductive system describing our world as the grounds for justifying our inference that the regularity will continue to hold in the future. Since Reichenbach's regularity is not found in our best deductive system, we are not justified in believing that the future will see an absence of gold chunks larger than a cubic mile. As the plutonium regularity presumably does follow from the best deductive system, we are justified in believing that there will never be a plutonium chunk larger than a cubic mile. Even if we put aside the circularity problem from the previous section, this response will not be satisfactory.

Given the possibility of the deviant worlds discussed above, as internal observers, we can never know which (set of) deductive system(s) best describes our world. Since it is both metaphysically and epistemically possible[28] that we occupy a world in which the electron-regularity has an expiration date, we cannot know what the final deductive system of our world will look like. If we are in a world in which the regularity holds eternally, then our final system will be one in which the regularity is an axiom or theorem.[29] If we are in a world in which the regularity is only temporary, the final system will not include it. We cannot know which system is the accurate description of our world until all the facts about our world are in. This entails that only an external observer looking at the totality of facts about a world can be in a position to know what the final axiomatic deductive system will be; the internal observer is *never* in a position to know. Since internal observers can never be in a position to know whether an observed regularity will be a part of the final deductive system, their beliefs that the regularity will persist can never be justified.

Further, the Humean can offer no explanation for the success of inductive inference beyond dumb luck. This is especially troubling when we consider just how lucky it is that we have thus far found ourselves in a world where the regularities we observe continue to hold. Based on the sheer number of worlds in which these observed regularities fail to hold at some time, it is extremely improbable that we occupy a world in which they will continue to hold. Given this fact, the Humean *ought* to expect inductive inference to fail, and she must chalk up its incredible success thus far as nothing more than a cosmic fluke.

From the perspective of a scientific realist, this does not sit well. One of the driving motivations behind scientific realism is the feeling that there must be an explanation for the success of science. The use of induction is a cornerstone of scientific theorizing and investigation. If the Humean cannot offer an explanation of the success of the inductive method, neither can she offer an explanation of the success of science.[30]

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[28] For the Humean

[29] Again, we are disregarding the problem of distinguishing accidental regularities that hold eternally from lawlike regularities.

[30] It is sometimes claimed in the literature that the Humean is no worse off than the non-Humean when it comes to explaining the success of inductive inference. However, this is

3.2.2.4 Ontological troubles

It is clear that the so-called "sophisticated" version of Humeanism faces a number of unique problems. But there is a more general problem with Humeanism that one of its commitments – namely, the commitment to quidditism about properties – is inconsistent with the view's motivations. Humeanism is motivated in part by the empiricist attitude that we should not be committed to the existence of what we cannot possibly observe. Since, the reasoning goes, we can only ever observe the *constant conjunction* between events and never the actual causal relation, we ought not have a metaphysical account of causation as anything more than constant conjunction. But in denying that there is any physical or causal necessity in the world, the Humean must deny that there is any necessary connection between what a property is and what causal relations it bears to other properties. So the Humean must maintain that properties are something over and above their causal profiles, and they are thereby committed to the view that properties have quiddities.[31]

A number of philosophers, such as Shoemaker (1997), Hawthorne (2001), and Bird (2007), have suggested that what physical properties *are* is determined, at least in part, by what they can *do*. We'll call views that fit this framework *dispositional* accounts of property-individuation. On these views, a physical property is a collection of dispositions, understood as the potential causal relations it can bear to other physical properties. Consider the property of being negatively charged. On the dispositional view, part of what it is to be this property is to have the capacity to attract positively charged things. Thus, on the dispositional view, there is a necessary connection between being

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not the case. The non-Humean need not admit the infinity of deviant worlds into her modal space, as she can instead deny that there could be non-empty worlds in which no laws of nature hold. Indeed this claim is in line with the evidence derived from the actual world that certain laws must be met before stable matter formation can occur. Of course, this same option is *not* available to the Humean, as it requires appealing to necessary connections between physical conditions and the existence of matter.

[31] Quiddities are to properties what haecceities are to individuals.

negatively charged and being able to attract things that are positively charged. Since the dispositional view of properties is committed to there being non-logical necessary connections in nature, it is incompatible with Humeanism. The Humean must deny that a property's causal profile plays any role in determining its nature. Thus, she must accept that there is something else that determines a property's nature, namely, an unobservable quiddity or primitive "thisness."

Humeanism's commitment to quidditism about properties is deeply at odds with its empiricist motivation. Whereas the Humean rejected a metaphysically realist account of causation in order to avoid a commitment to unobservables, she now finds herself committed to the existence of ineffable quiddities. Esfeld (2009) points out that although Humean metaphysics seems ontologically parsimonious at first glance, it is not parsimonious in the end.

Not only must the Humean be committed to quiddities, she must accept that there are physically indistinguishable possible worlds – in other words, there are differences that don't make a difference. Lewis recognized that quidditism leads to metaphysical underdetermination, which is what led him to consider the thesis of Ramseyan Humility. Quidditism entails that two worlds can share all of their physical features and yet differ only in terms of their quiddities. For instance, the role that negative charge plays in our world might be played by positive charge in another world, but the two worlds will share all of the same observable features. Since there will be multiple worlds that satisfy the Ramsey sentence describing the laws of our world, we can never know which of these worlds is our own.

Whereas the motivation for Humeanism seems to begin with the desire for deflationary metaphysics, it is clear that this desideratum cannot be obtained through Humeanism. In denying the notion of causal or physical necessity, the Humean commits herself to the existence of ineffable quiddities and differences that don't make a difference – hardly a metaphysics that can be called deflationary.

3.2.3 Why be Humean?

We have seen that even the best version of Humeanism is plagued with problems: it cannot be formulated non-circularly, it can offer no reasonable account of the laws of the special sciences, and it cannot explain the success of inductive inference, This plethora of problems leads one to ask a pressing external question about Humeanism: *Why be Humean?* The question, which Maudlin (2007) asks in a chapter title of his latest book, is not a rhetorical one, nor is it one to which he finds a satisfactory answer.

Maudlin characterizes Humeanism partially in terms of the doctrine of *Physical Statism*. Physical Statism is the doctrine that all facts about a world, including modal and nomological facts, are determined by its total physical state. It has the consequence that no two worlds can have the same total physical state but differ in their laws of nature. Maudlin argues that contemporary physics seems to offer clear counterexamples to this thesis. He considers the fact that cosmologists regard models of the field equations of General Relativity as physically possible universes. Minkowski spacetime is a model of the GR field equations,[32] but it is not a model *only* of GR laws. One could postulate a world in which Special Relativity exhausted the facts about spacetime structure and in which some other theory of gravitation held that would still have vacuum Minkowski spacetime as a model. These two empty Minkowski universes would share their total physical states but differ in their laws of gravitation. Since Physical Statism, the doctrine at the heart of Humeanism, appears to be in direct conflict with the assertions and practices of cosmology, it is unclear what could motivate the Humean view.

Maudlin considers Hume's own motivations, which relied in part on the semantic thesis that any non-analytic claims that go beyond the realm of the empirically observable are meaningless. But hardly any of the contemporary figures who accept Humeanism also accept a verificationist theory of meaning, and even fewer accept Hume's epistemological view that every simple idea must come from a simple impression. "The semantic theory that underlies Hume's own views has been thoroughly discredited," Maudlin writes. "Why should one have 'Humean scruples' any more?" I share in his bewilderment.

[32] In particular, it is the vacuum solution.

4. What a Structuralist Theory of Properties Could Not Be

4.1 Introduction

Causal structuralism is the view that, for each natural, non-mathematical, non-Cambridge property, there is a causal profile that exhausts its individual essence. A property's causal profile is the collection of conditional powers it bestows on its instances as well as its "backward-looking" causal features regarding what can cause its instantiation. Having a property's causal profile is both necessary and sufficient for being that property. It is generally contrasted with the *Humean* or *quidditistic view* of properties, which states that having a property's causal profile is neither necessary nor sufficient for being that property, and with the *double-aspect view*, which states that causal profile is necessary but not sufficient.[33] Motivated by a distaste for the metaphysical baggage of quiddities, the proponents of causal structuralism have detailed a number of convincing arguments against the Humean and double-aspect views. What these arguments get right is that our theory of properties cannot appeal to quiddities but must rather be a structuralist view. But appealing to the *causal* relations that physical properties bear to one another as determining their essence is crucially misguided. I offer several counterexamples from physics where the nature of a property seems to be determined in part by its higher-order mathematical features.

I conclude by suggesting that what is needed is a structuralist view of properties that is neither merely causal nor wholly dispositional,[34] but that incorporates a physical

[33] Of course, there is an opening in logical space for a view on which having a property's causal profile is sufficient but not necessary for being that property, but it is unclear what could possibly motivate one to hold this view.

[34] Dispositional essentialism, which is the view that all fundamental properties are purely dispositional, shares many of the same motivations as causal structuralism. And since it need not characterize dispositions only in terms of causation, it does escape some of the problems that causal structuralism faces. But since the cases I discuss are examples of

property's higher-order mathematical properties into its identity conditions. These structural mathematical features of properties do the work of quiddities without the idiosyncratic metaphysics.

4.2 Metaphysical accounts of properties

Positions on the natures of physical properties take the form of three main views:

Humean/neo-Humean view: Causal powers a property confers are not part of the property's essence. Though every property may have a causal profile, having the causal profile that it does is neither necessary nor sufficient for a property's being the property that it is.

Double-aspect view: Some or all of a property's causal powers are essential to it. Having a certain causal profile is necessary but not sufficient to determine a property's identity.

Causal structuralism: For each fundamental (natural, non-mathematical, non-Cambridge) property, there is a causal profile that exhausts its individual essence. Having a property's causal profile is necessary and sufficient for being that property.

The Humean view, most prominently defended by Lewis, entails that properties can play very different causal roles across possible worlds. The property of being negatively charged, for instance, could have failed to confer the power to attract positively charged things. Since different properties can share causal profiles on this view, the Humean must accept that there is something else that determines a property's nature, namely, an unobservable quiddity or primitive "thisness." Quiddities are by nature unobservable, as any observable features of a property are part of its causal profile, which the Humean takes to change across possible worlds. Notably, the Humean is not

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fundamental physical properties whose nature is determined in part by *categorical* mathematical structures, dispositional essentialism fares no better in the end.

committed to natural necessity, and it is its compatibility with Humeanism about causation that primarily motivates this view.

On the less popular double-aspect view, two properties may have the same causal profile, so a property's causal profile does not exhaust its individual essence. Since having the causal profile that it does is essential to a property's being the property that it is, properties cannot change their causal profiles across possible worlds. But since two or more properties can share a causal profile, the double-aspect theorist must still appeal to some additional entity in order to individuate and identify properties. So she too is committed to the existence of quiddities and to the metaphysical baggage that accompanies them. As the view is committed to necessary connections between properties and their causal profiles, it is incompatible with Humeanism about causation.

Causal structuralism, on the other hand, entails that the powers a property confers do not change across possible worlds. Defended by Shoemaker (1998) and explored by Hawthorne (2001), the view is generally seen as an empiricist approach to property-individuation and essence.[35] Nothing more than its causal profile is required for a property's transworld identity. On this view, of course, two or more properties cannot share causal profiles while remaining distinct from one another. The causal structuralist takes causation to be a fundamental part of the world. She is committed to a robust account of causation and thus to the existence of natural necessity. Still, her commitments remain less empirically objectionable than the quidditist's, as there is at least some opportunity to observe causal relations in the world, while there is in principle no chance of observing quiddities.

Arguments in favor of causal structuralism tend to focus on the unappealing consequences of the Humean and double-aspect views' commitments to quiddities. Two of the arguments for causal structuralism, the semantic argument and the epistemological argument, turn on the claim that causal structuralism is the only view that allows us to refer to and recognize physical properties. The epistemological argument says that if two

[35] It could also be defended on the purely metaphysical grounds that a commitment to natural necessity is better motivated and more appealing than a commitment to quiddities.

properties, A and B, shared a causal profile, we could never identify which property was the cause of some physical event. We don't have access to anything regarding a property's quiddity; all we can observe is its causal profile. Thus, if two properties share one, we have no way to distinguish between instances of one and instances of the other.

The semantic argument further draws out the consequences of profile sharing. If this possibility is allowed, then many statements we take to be true will turn out to be false, and some of our statements will be threatened by semantic indeterminacy. Consider the following case. We notice that every instance of some phenomenon C seems to be preceded by an instance of P. Our controlled experiments seem to vindicate the claim that "All instances of C are caused by P," and we then use P in statements of laws. However, not all instances of C are preceded by an instance of P. Some are preceded by an instance of B. So our claims about what causes C will turn out to be false. But the problem extends further. Given our belief in the lawlike claim, we may make statements that involve the phrase "*the* cause of C." These statements will fail to refer to anything, and our science will be compromised by semantic indeterminacy.[36] This undermines the project of science in that it limits the extent to which science can discover facts about the world, including those that are usually considered to be within the realm of science.

The metaphysical argument against quiddities is that they commit one to indistinguishable possible worlds, or "differences that don't make a difference." Quidditism entails that two worlds can share all of their functional and behavioral features yet differ only in terms of their quiddities. Needless to say, once we narrow our world down to some set of observationally indistinguishable possible worlds, it is impossible for us to find out which member is our actual world. Since there will be multiple worlds that satisfy the Ramsey sentence describing the laws of our world, we can never know which of these worlds is our own.

[36] Hawthorne himself is unmoved by this objection, as he seems to consider it a version of a skeptical argument. He responds that worlds containing quasi-duplicate properties are too far away from the actual world to be of much concern, and he admonishes us not to "throw out a metaphysical hypothesis on the basis of unlucky world arguments" (366).

Note that all of these arguments have to do with the ramifications of profile sharing. They support causal structuralism only insofar as it is the best view of properties that precludes this possibility. In the standard debate, it is assumed that causal structuralism is the only view – and therefore the best view – that prohibits profile sharing. I will, however, suggest another view that prohibits profile sharing while also avoiding the problems faced by causal structuralism. Since this view retains the motivations for causal structuralism while avoiding the problems it faces, it could even be taken as a friendly amendment to the view.

The problems facing causal structuralism include the lack of a unified notion of causation across the sciences, the likelihood that causation is not a fundamental feature of the world, and the fact that there are a number of physical properties whose causal profiles seem not exhaust their essences. Many of the problems that arise for the causal structuralist result from what seems to be a conflation of the *causal* with the *nomological*. While Shoemaker seems to think that these two things completely coincide, the examples I discuss show that the nomological actually subsumes the causal. One suggestion, then, is for the causal structuralist to broaden their view of what should be included in the profile that determines a property's essence. We ought to understand a property's essence in terms of its nomological profile rather than in terms of its narrower causal one. This proposed change accommodates the problematic cases that constitute counterexamples to the view as it is, and it avoids the obstacles created by prematurely assuming causation is a fundamental feature of the world.[37]

4.3 Problematic properties

There are three primary classes of properties that provide difficulty for causal structuralism:[38] properties of quantum systems, properties regarding the global structure

[37] Allow me to stress that I accept that causation is a metaphysically real and robust feature of the physical world. My concern surrounds the likelihood that it is not built into the fabric of spacetime but only emerges at more macroscopic scales.
[38] As well as for any version of dispositionalism.

of spacetime, and properties relating to conserved quantities.[39] We will address one example from each group.

4.3.1. Quantum Incompatibility

The first property that poses a challenge to causal structuralism is the quantum property of incompatibility. Incompatibility is a two-place relation that holds between a pair of quantum observables. The reader is likely familiar with the Heisenberg Uncertainty Principle. While its name indicates only an epistemic limitation, it is best understood as a metaphysical principle: no quantum system can simultaneously have a definite location and momentum. The properties of location and momentum form but one pair of incompatible properties. From the quantum formalism, it can be shown that there are infinitely many such pairs. When two observables are incompatible, they can never both be simultaneously instantiated with determinate values by a single system. What's more is that the explanation for this, and indeed our explication of the property of incompatibility itself, is at least partially mathematical. In order to get a better understanding of this, let us look at some basic background quantum mechanics.

The quantum formalism deals primarily with vectors in the type of vector space known as Hilbert space. Vectors in Hilbert space are physically interpreted as representing states of a quantum system, and Hermitian operators[40] on these vectors are interpreted as physically possible properties of the system. Every quantum system has a wavefunction, which gives the probability amplitude for all the states that the system might be in with respect to a certain property. The wavefunction evolves deterministically in Hilbert space according to the linear dynamics of the Schrodinger equation.

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[39] While all the counterexamples to causal structuralism addressed here are from physics, I do not wish to suggest that the special sciences are free of them. Indeed, I think a number of special-science properties will pose similar problems, especially those that are essentially probabilistic or related to equilibria.
[40] A Hermitian operator is a self-adjoint operator, meaning its matrix forms its own conjugate transpose.

Every physical system (i.e. every physical object, and every collection of such objects) is to begin with associated with some particular vector space. The various physically possible states of any such system correspond to vectors of length 1 in that system's associated space. Every such vector is taken to pick out some particular state. The states picked out by all those vectors are taken to comprise the possible physical situations of that system. In an N-dimensional space, any collection of N mutually orthogonal vectors in that space (that have a norm of 1) are said to form an *orthonormal basis* of that N-dimensional space. If for some particular operator O and for some particular vector $|B>$ the vector $O|B>$ generated by operating on $|B>$ with O happens to be a vector pointing in the same direction as $|B>$ then $|B>$ is said to be an *eigenvector* of O with *eigenvalue* α (where α is the length of the new vector relative to the length of $|B>$). A more intuitive way to picture this is to consider the basis made up of mutually orthogonal vectors. Think of these as axes in a coordinate system. A vector that lies along an axis will be an eigenvector of the property associated with the operator that takes vectors to that axis.

Measurable properties of a physical system are called *observables*, and they are represented by linear operators on the vector spaces associated with that system. Albert (1994) states the rule that connects those operators (and their properties) and those vectors (and their physical states) as follows:

> If the vector associated with some particular physical state happens to be an eigenvector, with eigenvalue (say) α, of an operator associated with some particular measurable property of the system in question (in such circumstances, the state is said to be an *eigenstate* of the property in question) then that state has the value α of that particular measurable property. (33)

States that are definite with respect to the value of a physical quantity are called *eigenstates* (this is always relative to some observable).

Not all operators on Hilbert space commute. Operators that do not commute do not share eigenstates, so they represent *incompatible* observables. Thus, a physical system cannot have definite values for both of their corresponding properties simultaneously. Necessarily, for two incompatible observables, if a system is in an eigenstate of one, it will be in a superposition of the other.

This higher-order property of incompatibility of two properties is defined in terms of the non-commutativity of their corresponding operators. The operators corresponding to spin in the x-direction and spin in the y-direction, for example, do not commute, so they represent incompatible observables. The incompatibility of a pair of properties entails that whenever a physical system is in an eigenstate of one it will be in a superposition of the other.

Causal structuralism says that a property's essence is exhausted by the set of causal powers it confers on its instances. But it is clear that the essence of quantum incompatibility is partially mathematical, specifically, linear algebraic. Any explication of incompatibility makes ineliminable reference to the non-commutativity of the operators representing the relevant properties. Commutativity is a mathematical notion that cannot be spelled out in any sort of causal terms, yet it is at the heart of what it is to for two properties to be incompatible.

Incompatibility clearly has causal consequences, as it governs the conditions that constrain the physical instantiation of the pairs of properties that have it. And pairs of incompatible properties exhibit stable dispositions. No physical system can ever simultaneously be in an eigenstate of two incompatible properties. But incompatibility is not merely a causal or dispositional property. The disposition of two incompatible properties to never be simultaneously instantiated with a determinate value follows from the categorical nature of incompatibility, which is characterized by the mathematical property of non-commutativity.

It would be very odd to think that the causal profile of incompatibility is essential to the property while its mathematical structure that is ascribed by the theory is inessential to it. The mathematical structure is more fundamental to the property's nature than its causal profile is, as the mathematical structure of the property actually entails its causal profile. Thus, thus mathematical structure of the property explains the property's causal behavior, but the causal profile cannot be said to explain the mathematical structure.

Though incompatibility is not a wholly causal relation, it is one of the conditions under which the property of superposition is instantiated. This means that the property of superposition creates a further problem for the causal structuralist. Since the causal structuralist includes in a property's causal profile its "backward-looking" relations (i.e. the conditions that result in its instantiation), the fact that a physical system instantiates the superposition property whenever it is in an eigenstate of an observable that is incompatible with respect to some other observable seems to be just the sort of condition that ought to be included in the essence of superposition.

It is not the case that a physical system's being in an eigenstate of spin along the x-axis *causes* it to be in a superposition with respect to spin along the y-axis. Nor is it the case that the incompatibility of spin along the x-axis and spin along the y-axis causes it to be in a superposition of spin-y states. Rather, it is a mathematical necessity that can be derived from the linear algebraic formalism of the theory.

Since the categorical, mathematical property of non-commutativity is an essential constituent of incompatibility, the conditions under which superposition is instantiated are not merely causal.

4.3.2 Global properties of spacetime

The second type of challenging property concerns the global structure of spacetime. These properties pose a special challenge for causal structuralism in that they are instantiated by spacetime itself rather than at some location within spacetime. As we saw in the previous section, causal relations hold only between objects, events, or points within spacetime. While there are some properties of spacetime that can be cashed out as possible causal relations among spatio-temporal points, it is unlikely that we can analyze all spacetime properties in this way. Consider that the path of a beam of light is bent in the vicinity of a massive object. What is the explanation for this?

Colyvan (1999) suggests that the explanation is a geometric one. "It's not that something causes the light to deviate from its usual path; it's simply that light travels along space-time geodesics and the curvature of space-time is greater around massive objects." While being in the vicinity of a massive object is clearly one of the conditions under which a beam of light will bend, it is by no means obvious that it is causal condition. In fact, there are special difficulties with understanding the relationship between massive bodies and paths of light as a causal one.

Though the causal structuralist could try to argue that the mass of the body *causes* spacetime to curve, this route looks unpromising. There is no exchange of energy between the massive body and spacetime itself, nor between spacetime and the bent path that light follows. Worse, there are non-Minkowski vacuum solutions to the Einstein equations. This means that there are empty curved spacetimes. As Colyvan says, "What then is causing the curvature in the vacuum solutions case? There is nothing *to* cause it!" (4).

Further, the relation between the distribution of mass and curvature of spacetime is not asymmetric, as we expect causal relations to be. We can derive the distribution of mass from the curvature of spacetime and vice versa. Colyvan emphasizes that the covariance between mass and spacetime curvature should not be misconstrued as causation. There are numerous examples of covariance where no causal relation is present. For instance, the behavior of parallel lines co-varies with the type of space in which they are embedded, though it is not the case that one causes the other.

Though we can certainly say that the curvature of spacetime is in some sense *due to* the presence of massive bodies, we can only speak of the massive bodies as *causing* spacetime curvature in a very loose and imprecise way. There does not seem to be an analysis of causation available that would allow us to understand massive bodies as causing spacetime curvature but rule out that purely mathematical properties could bear causal relations to one another. It seems as though any analysis of causation that takes spacetime curvature as causing light to travel along geodesics would also have the consequence that applying projection operator $\mathbf{P}_x$ to a vector *causes* it to be projected onto the x-axis. In effect, we will have exchanged causation for the logical entailment relation.

4.3.3. Conservation properties

The third kind of property that poses a challenge to causal structuralism is the kind of property that represents a conserved quantity. The first theorem in Noether's (1918) showed that every continuous symmetry of a physical theory or system has an associated conserved quantity. The shift symmetry of space leads to the conservation of linear momentum, the rotational symmetry of space is responsible for the conservation of angular momentum, and the shift symmetry of time corresponds to the conservation of energy[41] (Lange 2007). Further, these symmetry principles can be understood as meta-laws that govern the conservation laws and explain why they hold. It is this last example that I will focus on here.

The local conservation of energy in closed systems can be mathematically derived from the assumption of this symmetry, when the time-translation symmetry is a finite-parameter continuous group (such as the Poincare group). The shift symmetry of time can be described as the fact that the laws of physics do not change over time. Whether one accepts a Humean or non-Humean view of laws, most can agree that laws of nature are simply not the sorts of things that can change over time. If we discover that some regularity changes over time, that is tantamount to discovering that it was never a law in the first place. Rather, it was merely a contingent fact. So if laws of nature cannot change over time, then any metaphysically possible world is one that instantiates the shift symmetry of time. Since the conservation of energy follows from the shift symmetry of time (combined with an assumption of a finite-parameter group of symmetries), a necessary fact, it is necessary that energy is a conserved quantity in any closed system in a spacetime whose translations are defined by a finite-dimensional symmetry group.

[41] When the symmetry group of the translations is finite-dimensional.

From this, I'd like to conclude that part of what it is to be energy is to be a conserved quantity (under the relevant conditions). Of course, some will accuse me of making the dubious move from energy's necessarily being a conserved quantity to its essentially being a conserved quantity. But this does not seem like the sort of case in which that is problematic. We are not talking about an unintuitive Cambridge property of energy – this is something that really does determine its nature. Consider at least what the causal structuralist ought to think given their original motivations. The causal structuralist wants to assert a necessary connection between what a property *is* and what it *does*. She wants the nature of a property to be those features of the property that determine how it behaves in the world. The conservation of energy does just that. It determines that part of what energy does is to remain constant in closed systems.

That energy has the property of being a conserved quantity under the relevant conditions bears on what possible measurements we could make on any system that instantiates the energy property. In this way, the higher-order property of being a conserved quantity bears at least some connection to the causal profile of energy. It is not the sort of thing that could be measured as anything other than constant over time in a closed system. So the conservation property is something that the causal structuralist must accept is part of energy's essence. But what exactly is the conservation property? Is it wholly causal?

It does not seem that we can understand the conservation of energy as a wholly causal process. That energy is conserved is a property of the universe as a whole. Causation, on the other hand, is generally taken to be a local process rather than a global one. We will lose this locality if we try to say that the energy state of the entire universe *causes* all future energy states to be equal. Further, since we can derive past states from future ones just as we can derive future states from past ones, the conservation of energy across spacetime does not bear the temporal asymmetry we expect of causal processes.

How then should we understand conserved quantities? To be a conserved quantity is to be invariant under some transformation or set of transformations. Invariance under transformation is a mathematically defined notion that comes from group theory. Even though this higher-order property of invariance over shifts in time can be construed as conferring causal powers related to possible measurements of systems instantiating the energy property, those powers are explained by the physical property's higher-order mathematical property of invariance. Since the property of invariance is inherently mathematical rather than causal and it is partially constitutive of essence of being energy, this seems to constitute another example of a physical property whose essence is not exhausted by its causal profile.

4.4. Objections

One might object that non-causal aspects of the relevant physical properties I have pointed out are not mathematical at all but merely physical. For instance, it could be argued that the time translation used when measuring the conservation of energy is a wholly physical translation that has nothing to do with the corresponding mathematical notion of translation in a geometric space. Analogously, my opponent might argue that the physical property of being a conserved quantity has nothing to do with the mathematical notion of invariance under transformation. This is certainly a path that is open to my opponent, though it requires much evidential support, as science does not seem to motivate such a distinction. Further, if my opponent succeeds in showing that the higher-order features of these physical properties are indeed *not* mathematical, they will not have thereby shown them to be causal. Nonetheless, I respond to this inchoate objection by showing my opponent's distinction to be unmotivated.

I deny that there is a compelling distinction to be made between purely physical and mathematical versions of the same property. One can accept that the relevant time translation and conservation properties are physical while still acknowledging that the notions of symmetry and invariance are in some respect inherently mathematical. These notions were originally developed in the mid to late 19th century within the formalism of group theory and only later found to be useful in spacetime physics, and we count them as examples of the successful application of mathematics to physics. The physical reality of these properties does not entail that they are *solely* physical, especially given the *prima* *facie* evidence that when we use them, we are using mathematical notions that have been found to be applicable to physics. Someone who wants to completely divorce physical symmetries and translations from the corresponding, well-defined mathematical notions must provide a non-question-begging argument as to why we ought to think that, in each case, there are really two distinct, unrelated notions, when we seem to be able to make do with a single unified notion.

Though many people have a strong intuition that there is a clear distinction between the purely physical and the purely mathematical, the science itself does not seem to motivate such a distinction. In fact, it makes drawing such a distinction rather difficult. This is especially true with respect to the objects of theoretical physics. Resnik (2000) notes many of the more fundamental physical objects share at least as many relevant properties with mathematical objects as they do with familiar physical ones. Quantum particles often fail to have definite locations, masses, velocities, and spin. And quantum mechanics lacks the means to tag particles before an interaction and re-identify them after. This leads many to deny that quantum particles are individuals, which is often taken to be a mark of physical objects. In quantum field theory, the number of particles present in a given region of spacetime fails to be determinate, as particles emerge from excitations of the field, which is itself understood as a distribution of irreducible probabilities. Resnik takes these examples to "break down the epistemic and ontic barriers between mathematics and the rest of science." Certainly, this is not decisive, but it does show that my opponent must provide some reason, beyond unsupported hunches, to believe that a clear distinction between the mathematical and the solely physical can be drawn in each case that I raise.

Another possible objection is that I have been too hard on the causal structuralist. Elias Okon suggests that I might more charitably interpret "causal profile" in a way that is broad enough to including any empirically detectable features or relations among properties. Certainly, if we were to interpret causal profile as such and use a suitably broad understanding of "empirically detectable" the causal structuralist's problems would disappear. But is this a reasonable understanding of the notion of causal profile? I think that it is not.

The conflation of the causal with the broadly empirically detectable does no favors to naturalistic metaphysics. The notion of causation is a useful one that we should not jettison. If we weaken it so much as to include any and all empirically detectable relations, we will lose the useful relation that does extensive work in the special sciences.

We even need the normally strict understanding of causation to make sense of why quantum entanglement is problematic. Quantum entanglement is an especially mysterious phenomenon, precisely because Bell's theorem shows the correlation between the states of entangled particles *a* and *b* cannot be understood in terms of *a* causing *b* or vice versa or in terms of *a* and *b* having a common cause. Quantum entanglement is thus taken to be a special sort of relation particularly because it cannot be understood as causal in any usual sense. If we broaden our notion of causal relation so as to include any empirically detectable necessary relation, we will lose a useful notion that allows us to distinguish between quantum entanglement and standard causal relations, and thus to explain why the relationship of entanglement is so perplexing.

4.5. Is causation fundamental?

As causal structuralism aims to characterize all physical properties in terms of their causal profiles, it presupposes that there is some suitable notion of causation that is foundational enough to do this work. While causal structuralism is not necessarily committed to the claim that causation is a fundamental feature of the universe, we might question the prudence of using a non-fundamental feature of the universe to characterize the nature of all physical properties, including fundamental ones. If causation is not fundamental to our physical universe, we ought to expect there to be some physical properties that are more fundamental than causation, and that therefore cannot be understood in terms of causation. Indeed, the cases I have raised seem to be just these sorts of properties. But even if the causal structuralist finds a way to accommodate these properties, the question of what account of causation is best suited to the view remains to be settled.

Causal structuralism treats causation as a fundamental, primitive notion. However, other than acknowledging a commitment to natural necessity, defenders of the view fail to offer an explicit account of causation. Perhaps, then, we ought to assume that the notion accepted is one that conforms to our most basic folk and philosophical understanding of causation. While intuitions surrounding causation differ greatly, there are two features that are generally part of our basic concept of causation. They are the following:

(1) Causal relations exist within spacetime (i.e., they hold between objects and events that are located in spacetime).
(2) Causality presupposes directionality of time[42] (i.e., there exists a time-asymmetry, and backward causation is likely not possible. A cause must precede its effects.)

We can use the term "folk causation" to refer to any concept of causation that respects these two features. While folk causation is a notion that appears throughout the special sciences and is used within them to formulate predictions and generalizations, it is not a notion that plays any scientifically rigorous role in fundamental physics. As we will see in the next section, there are a number of physical properties that simply cannot be accounted for within the framework of folk causation. One reason for this is that many laws of physics and the properties they describe are time-reversal invariant. They work the same way forward and backward in time. A concept that presupposes a directionality of time is therefore the wrong sort of thing in terms of which to characterize these properties. While it is true that some theories of quantum gravity, most notably causal sets theory, do build causation into the fabric of spacetime at the fundamental level, this should not offer much solace to the causal structuralist. At best, the plausibility of their

[42] Of course, this directionality need not be part of the fundamental structure of spacetime.

view hinges on the small chance that causal sets theory will turn out to be the correct theory of quantum gravity.

This brings us to our second option, which is to assume the notion of causation that is used in spacetime physics. Unfortunately, though this notion of causation is well defined, it differs importantly from the folk notion and is very far from any metaphysically robust conception of causation. It cannot be made to do the necessary work that the special sciences require of causation.

The notion of causation used in spacetime physics is a topological one. It is defined in terms of the light-cone structure of the Lorentzian manifold. A light-cone is a structure that represents the edges of the region of spacetime that can be reached by light traveling away from the point of origin. Since the speed of light is the maximum propagation speed of information in our universe, points outside the light-cone are not reachable from the point of origin and vice versa. Thus, all and only points inside and along the light-cone are considered causally connected to the point of origin. What is important for our purposes is that this concept of causation is too course-grained to do the work of causation in the special sciences. It can offer no interesting distinction between two things that lie inside the observer's light-cone, and this is exactly the distinction that is needed to accommodate the requirements that the special sciences make on the notion of causation.

Consider the sorts of causal claims that are made within the special sciences: Prolonged UV exposure causes cancer, consuming more calories than you burn causes weight gain, and earthquakes can cause tsunamis. Could these facts be stated in terms of the notion of causation from spacetime physics? Since all we can appeal to are the spatio-temporal relations among points in the manifold, we cannot even differentiate between co-located properties, where only some of which are causally related to a future event (in the special-sciences sense). The causal relation that is defined within special relativity cannot give us the tools we need to formulate basic chemical and biological facts. Thus, the causation concept from spacetime physics fails to provide a sufficient framework within which to characterize all physical properties.

I do not claim to show that no satisfactory account of causation is available to the causal structuralist. However, it does seem clear that simply adopting a naïve understanding of causation will not do. To succeed, the causal structuralist must find an account of causation that is foundational enough to characterize all physical properties yet fine-grained enough make the necessary distinctions required of causal relations in the special sciences. Perhaps an account that fits these criteria is possible, but formulating one is by no means a trivial task.

4.6. Where to go from here

What these examples have in common is that they each point to a physical property whose essence is at least partially constituted by a higher-order mathematical property. Causal structuralism has the right idea that the nature of a property should be understood in terms of the (empirically discoverable) necessary relations it bears to other properties. What it does wrong is assume that these relations are always causal. Causal structuralism naively assumes that there is a clean divide between the physical and the mathematical, which ignores the complex mathematical nature of contemporary physics.

What is needed is a structuralist account of properties that is not merely causal, but that incorporates a physical property's higher-order mathematical properties into its essence. A view of this sort does not fit cleanly into the traditional trichotomy of views, but it would maintain the motivations for causal structuralism. It likely precludes the possibility of a property having different causal profiles across possible worlds, since the property's mathematical relational essence would necessitate its causal profile. It would probably disallow profile sharing, as it is unlikely that two physical properties would share exactly the same higher-order mathematical structure. If we did find two such properties, we could always incorporate causal powers back into a property's essence, as long as we acknowledge that these causal powers do not exhaust its essence. This new theory would maintain the empiricist spirit of causal structuralism while avoiding both the pitfalls associated with causal structuralism and with views committed to quiddities.

5. Metaphysical Dependence: The Role of Mathematical Structure in Physical Modality

5.1. Introduction

The world is fundamentally a modal place. Physical systems have modal properties, and laws of nature have the force of nomological necessity. We must posit an objective physical modality in order to understand such things as laws of nature, causation, equilibria, and probability. These modal notions are necessary to make sense of our best scientific theories, and no scientific realist can do without them. But how is the scientific realist to account for modality? We saw in Chapter 3 that the Humean view of modality cannot account for certain genuine scientific possibilities, such as a vacuum Minkowski spacetime being a model of two different laws of gravity. We also saw that the Humean view fails to be naturalistically motivated. Thus, the scientific realist is led to reject Humeanism and embrace natural necessity.

Once the scientific realist embraces natural necessity, how should she account for the modality of the physical world? She might be tempted either to accept that the modality of the physical world is primitive or to fall back on Armstrong's account of natural necessity. While these accounts are superior to Humeanism in their ability to accommodate the robust physical modality that science requires, necessity remains a mysterious notion on both of these views.

In the previous chapter, I hinted at a view of physical properties that has consequences for what the scientific realist should say about the nature of physical modality. The essences of physical properties are determined in part by the mathematical structures of the laws that feature them. Properties derive their nomological limitations from these structures and are then characterized both by their nomological roles and the abstract structures that define and explain them.

With this view on the nature of physical properties in mind, I argue that the modal properties of the physical world derive from the mathematical structures that underlie the properties of physical systems and structure the systems themselves. I also argue that these mathematical structures should be taken to underlie the *modal* properties of physical systems. Just as mathematical structures define physical properties and sketch the limits of what they can and can't do, these same mathematical structures provide the basis for the nomological necessity of the physical world.

This view of physical modality provides an answer to another question that the scientific realist faces – one that might initially appear unrelated to the nature of physical modality. This is the question of how to account for the role of mathematics in the sciences.

It is hard to dispute what Eugene Wigner called "the unreasonable effectiveness of mathematics in the natural sciences." Mathematics plays an indispensible role in our modern scientific theories. As we noted in the previous chapter, much of the content of theoretical physics is mathematical; jokes abound that the only laboratory equipment that theoretical physicists require is pencil and paper. How can it be that mathematics, the study of what is often taken to be an abstract realm of structures and relations, is so relevant to our study of the concrete physical world? Scientists not only model the empirical world mathematically, they use mathematical structures to make inferences and novel predictions about it. What could explain the astonishing success of applying mathematics to physical systems? Call this the applicability problem. Long ignored in the philosophical literature, it was re-popularized as a philosophical issue by Steiner (1978), (1989), (1995), (1999), and it has been more recently addressed by Colyvan (2001), Pincock (2004a), (2007), and Bueno and French (2010).

The third problem that my view bears on is how to account for the prevalence of non-causal explanations in science. Colyvan (2001a) points to several examples of paradigmatically non-causal scientific explanation. The first is the explanation of the fact that, at any time *t*, there are two antipodal points on the surface of the earth that have exactly the same temperature and barometric pressure, which is due to a theorem in algebraic topology. The second example is the geometric explanation of the Fitzgerald-Lorentz contraction, which appeals to such non-causal, geometric features and entities of Minkowski spacetime, such as the Minkowski metric (51). The third example is the geometric explanation for the bending of light around massive bodies, which was addressed in the previous chapter.

While causal entities may figure into parts of the explanation in each of these examples, the explanations do not reference *only* causal entities. I contend that these examples of non-causal explanation can be understood as instances of mathematical entities and relations playing an indispensable role in scientific explanation.

My argument proceeds by way of an analogy between the no-miracles argument for scientific realism and the indispensability argument for mathematical realism. The enhanced indispensability argument and cases supporting it give us reason to think that facts about mathematical structures and relations explain and predict features of the physical world. Thus, there is an important parallel between the role of unobservable entities and the role of mathematical structures in science. Just as unobservable entities are usually taken to explain the behavior of observable entities when they *cause* such behavior, mathematical structures cannot be explanatory unless they bear some determination relation to the observable structures they are taken to explain. I conclude that we must posit a relation of metaphysical dependence between mathematical structure and modal physical structure.

The view that the modality of the physical world derives from the features of mathematical structures that physical systems instantiate or approximate has three main benefits: (i) it is a naturalistic account of physical modality, (ii) it offers a straightforward solution to the applicability problem, and (iii) it explains the prevalence of non-causal explanations in science. Because the view provides a unified solution to these seemingly disparate puzzles, it scores well with respect to the standards for naturalistic metaphysics outlined in the first chapter.

I discuss the logical properties of the *metaphysical dependence* relation and explain why it is neither mysterious nor threatening to the spirit of naturalism. I offer several examples of scientific explanations that tacitly appeal to metaphysical dependence, such as the explanation of time dilation by appeal to the Lorentz-invariance of spacetime. Finally, I show that my account is better motivated and less *ad hoc* than the alternatives by appeal to the fact that the metaphysical dependence relation is independently motivated by a number of issues outside the philosophy of science. I conclude by speculating about issues on which my view of physical modality sheds light, such as the usefulness of computer simulations in counterfactual modeling.

5.2. No-Miracles Argument for Scientific Realism

The no-miracles argument is an argument for scientific realism. Its name derives, of course, from Putnam's famous quote, "The positive argument for realism is that it is the only philosophy that doesn't make the success of science a miracle."[43] I characterize scientific realism as a commitment to the existence of the entities described by our best scientific theories, even if those entities are unobservable, and to the properties that such theories ascribe to them. The thesis of scientific realism has been described in a number of ways, not all of which use the language of "observables" and "unobservables." However, all descriptions of the realist position incorporate some version of these two central claims: i) The aim of science is something more than mere empirical adequacy or saving the phenomena, and ii) there is some correspondence relation between the contents of theories and reality.[44]

The argument goes that many of science's successes would be miraculous if not for this correspondence relation between theories and reality. These successes include science's ability to make predictions, offer explanations, and unify seemingly disparate

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[43] Putnam (1975a, 73)
[44] Though this relation can be cashed out in any number of ways – as truth, or partial isomorphism, for instance – the important characteristic of realism is that it posits some version of the correspondence relation.

phenomena. Patterns in data are projectible using scientific knowledge, and more importantly, scientific theories are able to make *novel* predictions; they predict things that have not previously been observed. Science offers explanations for observable phenomena, and these explanations often make reference to unobservable entities. Were these entities to be mere theoretical constructs, the success of science would be deeply mystifying. Science also aims at unification, and theories are judged by how well they unify phenomena that seem disparate at the empirical level. The following sections will take a closer look at each of these scientific capacities, and delineate the ways in which realism is better equipped than anti-realism to explain their success.

5.2.1. Novel Prediction

Before delving into theoretical accounts of novel prediction, let us consider two paradigm cases of it: General Relativity's prediction that light passing by massive bodies would bend and the prediction of Neptune's existence and location by Newton's law of universal gravitation.

In 1915, Einstein published his first work on the theory of General Relativity. A consequence of the theory was that light travelling by massive bodies would appear to an observer to be bent at a certain angle. One of GR's innovations was the covariance between mass and the curvature of spacetime. Since light travels along spacetime geodesics, and the curvature of spacetime is greater around massive bodies, the theory predicts that the path of a beam of light in the vicinity of a massive object will bend in accordance with the mass of the object: the greater the mass, the greater the bending. Arthur Eddington first observed this result during a solar eclipse in 1919, four years after Einstein published his theory. When Eddington observed the path of light from a nearby star as it passed in behind the sun, he found that the beam bent at the exact angle predicted by General Relativity.

The second example of novel prediction concerns planetary orbits. Discrepancies between calculations and data for Uranus's orbit led astronomers Le Verrier and Adams to independently postulate a hidden planet exerting a gravitational pull on Uranus. Using

Newton's law of gravitation, they calculated what the perturbations on Uranus's orbit would be given the location of the hypothesized planet. When they turned their microscopes on the sky, the planet was in the exact location predicted.

The idea behind the no-miracles argument is that these predictions would be miraculous – what Smart (1963) called "a cosmic coincidence" if the theories that made them were not somehow latching onto underlying features of reality. But how exactly does realism explain the ability of scientific theories to make novel predictions? I favor the account put forth by Ladyman and Ross (2007): "Since some theories have achieved novel predictive success our overall metaphysics must explain how novel predictive success can occur, and the explanation we favor is that the world has modal structure which our best scientific theories describe" (79). Successful scientific theories make novel predictions by accurately capturing some aspect of the physical world's modal structure. There are necessary connections among certain events, objects, and properties in the world. Scientific theories uncover these relations, and this is what accounts for their predictive success. General Relativity was able to successfully predict a novel phenomenon by identifying the necessary connection between massive bodies and spacetime curvature.[45] The necessity of the connection explains why Eddington, given his intention and the quality of his equipment, *could not have failed to* observe the relevant phenomenon. The restriction that curved spacetime places on possible paths of light is a modal one. Light can travel only the paths allowed by the curved geometry of spacetime. In other words, the light Eddington observed didn't just *happen* to bend in exactly the way Einstein's theory predicted; it *had* to. Scientific theories make novel predictions by accurately capturing the necessary connections between certain physical properties.

Novel prediction is dialectically important in the realism debate since its instances cannot be explained by the theorist's intent to account for relevant data. When a theory in question predicts a previously observed phenomenon, the prediction cannot be taken as

[45] In the Neptune case, Newton's theory got it right with respect to the necessary connection between planetary orbits and gravitational pull.

evidence for the theory's truth, since the theory could have been specifically constructed so as to ensure that it entails the proper predictions. On the other hand, that a theory is able to make a *novel* prediction reflects the fact that it has correctly captured some part of the world's modal structure.[46]

So what exactly counts as novel prediction? Worrall (1994) suggests that novel prediction occurs when "theories designed with one set of data in mind, have turned out to predict, entirely unexpectedly, some further general phenomenon" (4). This view accurately picks out the features of novel prediction that make it relevant to the realism debate. Put another way, the view picks out what is dialectically important about novel prediction. But it is not clear that these features are really what is metaphysically important about novel prediction. Worrall's characterization has been criticized, for instance, for making novel prediction dependent on the contingent psychological states of the theorist. In response, Ladyman and Ross offer a modal account of novel prediction. According to them, "That a theory *could* predict some unknown phenomena is what matters, not whether it actually *did* so predict" (2007). Clearly this picture would not satisfy a scientific anti-realist who eschews any commitment to modal metaphysics. But once we have accepted scientific realism, it seems clear that what matters is the nomological possibility that, given the structure of our world, a theory could have made a novel prediction.

5.2.2. Explanation and Unification

Our discussion of novel prediction shows the difficulty that the anti-realist faces in accounting for the success of science. But the anti-realist's trouble is not restricted to questions meta-scientific. The anti-realist is also at a disadvantage when it comes to explaining empirical phenomena. There are two kinds of genuine scientific explanation to

[46] It is not clear how the anti-realist can account for the fact that some theories make novel predictions. Their most common response involves denying that this fact needs to be explained.

which the realist has better access: (1) causal explanation and (2) theoretical or unificationist explanation.

The scientific realist is in a better position than the anti-realist to offer causal explanations of empirical phenomena. Offering a causal explanation involves giving the (often contingent) causal history of some event. Sometimes, unobservable entities are causes of observed phenomena, and properties of unobservables explain features of observed phenomena. Consider the explanatory role of wave-particle duality in causing the interference patterns in the double-slit experiment. As the anti-realist refuses to posit unobservable entities, she cannot appeal to particles or their properties in her causal explanations. She can only offer a causal explanation of an observed phenomenon if its cause is also observable. Thus, she is left with a dearth of explanatory resources even for events in the observable world.

The second kind of scientific explanation that is better suited to realism is explanation by way of unification within some theoretical framework. Friedman (1981) characterizes theoretical or unificationist explanation as "the derivation of properties of a relatively concrete and observable phenomenon by means of an embedding of that phenomenon into some larger, relatively abstract and unobservable theoretical structure." Since the anti-realist again resists positing such abstract theoretical frameworks, she cannot appeal to them in her explanations. What's more, argues Friedman, the realist is better confirmed even in her knowledge of the empirical world than the anti-realist is. A theoretical structure that plays an explanatory role in many diverse areas of science gains confirmation from all these areas, thereby strengthening our knowledge of the observable phenomena it unifies. Thus, the realist is better confirmed in her knowledge of the empirical world, which is the very kind of knowledge at which science aims according to the anti-realist.

As we have seen, the power of a scientific theory to explain and predict empirical phenomena results from how well it captures the modal structure of the world. Since this often involves unifying empirical phenomena in an abstract mathematical model, capturing the modal structure of the world sometimes requires positing unobservable entities. It also requires us to take seriously the notion of nomological necessity, as features of unobservables only explain patterns in observable data if they genuinely cause those patterns. Mere correlations are not explanatory. An explanation of the fact that light bends when passing by massive bodies that appeals to the correlation between massive bodies and the bending of light is no explanation at all. The true explanation appeals to the curvature of spacetime, its necessary connection to massive bodies, and its necessary determination of possible paths. Thus, only a scientific realist who is committed to a robust notion of natural necessity can fully account for the ability of theories to explain and predict patterns in the observable world.

5.3. Indispensability Argument

We saw that the no-miracles argument for scientific realism commits us not only to unobservable entities but to a necessary connection between the unobservables and the observable phenomena they are posited to explain. We now turn to the enhanced indispensability argument, so that we may demonstrate the parallels between the two arguments. I suggest that, just as in the case for scientific realism, the argument for mathematical entities commits us not only to the existence of the entities themselves but to a necessary relation between the entities and the empirical phenomena they predict and explain. Let us consider Colyvan's (1999) argument for mathematical realism:

Colyvan's Enhanced Indispensability Argument (EIA):

1. We ought to have ontological commitment to all and only those entities that are indispensable to our best scientific theories.
2. Mathematical entities are indispensable to our best scientific theories.
3. Therefore, we ought to be ontologically committed to mathematical entities.

The first premise follows from Quinean naturalism, which is the view that there are no non-scientific standards that we can use to assess our ontological commitments, and the second is supported by cases such as the ones discussed in the following section.

Before turning to the supporting examples, let me add an additional caveat. Mathematical entities are indispensable for the prediction and explanation of *modal* facts. The explanations into which they figure are explanations of possible and necessary features of empirical systems. We now turn to four examples supporting math's indispensability to the sciences.

5.3.1. Mathematical structure and novel prediction: Glashow-Weinberg-Salam model

In 1979, Steven Weinberg, Sheldon Lee Glashow, and Abdus Salam received the Nobel Prize in physics for their unification of the electromagnetic force and the weak force. In their search for an underlying mathematical structure that could unify the two forces, the physicists found that the relations between these forces and their carrier particles could be fully embedded within the $SU(2)\otimes U(1)$ gauge group. But the isomorphism between the structure of the forces and the symmetry group was not a perfect one. After the embedding, there remained two unmapped nodes where additional particles should have been.[47] The resulting electroweak theory postulated the W boson necessary to explain beta decay – what they were originally seeking to explain – as well as the previously unobserved and unknown Z boson. No one, including these three, had hitherto hypothesized the existence of a particle with the properties of the Z boson. But in 1983, experiments at CERN confirmed its existence. The electroweak theory successfully predicted the existence of a particle that no one had previously expected to find. The theoretical unification of known particles within a mathematical framework allowed for the prediction of a novel empirical entity, and the mathematical structure of the gauge group was seemingly indispensable to its discovery.

[47] One of the nodes' relations matched the properties of a particle they were expecting to find. The other predicted a particle with properties that they had not expected to find.

5.3.2. Mathematical structure and scientific explanation: Hexagonal honeycomb and the Honeycomb Theorem

The following three examples are all instances of mathematical entities or relations playing an indispensible role in the *explanation* rather than *prediction* of empirical phenomena. The first example, from Lyon and Colyvan (2008), regards the hexagonal structure of hive-bee honeycomb and the honeycomb proof in geometry. Consider the question of why hive-bee honeycomb is always divided up into hexagons as opposed to some other regular polygon. There answer is two-fold:

1. Selection favors bees that minimize the amount of wax they use to build their combs over bees that use more energy than necessary by building combs with excessive amounts of wax.[48]
2. Any partition of the plane into regions of equal area has a perimeter greater than that of the regular hexagonal honeycomb tiling.

Part (1) of the explanation makes obvious evolutionary sense. Given that finite resources place limitations on survival, natural selection favors efficiency over inefficiency. Organisms that use more energy than necessary to complete a task will be less fit than conspecifics that use only what they need. Bees who produce more wax than required do so at the cost of not being able to complete other tasks necessary for the survival and reproduction of the germ-line. Darwin explained the structure as follows: “That motive power of the process of natural selection having been economy of wax; that individual swarm that wasted least honey in the secretion of wax . . .succeeded best” (Hales, 2). Thus, selection favors hives whose wax production is the minimum required for honeycomb production. This part of the explanation is clearly empirical.

Part (2) of the explanation, on the other hand, is purely mathematical. Hales published his result in *Discrete & Computational Geometry*, a journal of pure

[48] Lyon and Colyvan

mathematics. Previously known as the Honeycomb Conjecture[49], the honeycomb theorem states that the hexagon is the polygon that tessellates a plane with the smallest resulting perimeter. As a theorem of geometry, this is neither a contingent fact, nor an exclusively biological one. Rather, it is a necessary fact about possible partitions of the plane into regions of equal area. No such partitions can have a perimeter less than that of the hexagon.

The fact that honeycomb structures are hexagonal is not merely a contingent fact but a necessary one that carries the force of a law of nature. The honeycomb proof's explanandum is not just why bees *happen* to have hexagonal honeycombs; it is why they *had* to have them. Ceteris paribus, bee populations that use hexagonal tiling will be better off than bees that use square or triangular tiling to create their honeycombs. Given natural selection, the equilibrium state is one in which hive bees produce hexagonal honeycomb. This is a law of biology. The mathematical necessity of this result plays an indispensible role in the explanation of the biological necessity of the honeycomb's equilibrium structure.

5.3.3. Mathematical structure and scientific explanation: Squaring the circle

Consider the challenge of squaring the circle, *i.e.*, of drawing a square that has the same area as a circle, using only a compass and straightedge, in a finite number of steps. It cannot be done. It is a modal fact about our world that it is not possible to square the circle. What explains this fact?

The formula for the area of a circle is πr^2. Since π is a transcendental number, squaring the circle involves generating a transcendental ratio, namely $1/\sqrt{\pi}$. But only algebraic ratios can be constructed with just a compass and straightedge, namely those constructed from the integers with a finite sequence of operations of addition, subtraction, multiplication, division, and square roots. The explanation of why the circle cannot be

[49] Hales published a proof in 1999.

squared is that doing so would require constructing a transcendental ratio, and only algebraic ratios can be constructed from compass and straightedge alone.

While this example is a simple one, its simplicity illustrates how easily we can construct examples of empirical phenomena whose existence is forbidden by mathematics. It would be equally straightforward to create similar examples using graph theory (e.g. the bridges of Konigsberg, the three-utilities problem), knot theory, or theorems of circle and sphere packing. While they may not obviously count as instances of mathematical explanations in *science*, uncomplicated examples of empirical phenomena whose necessity or impossibility are explained by theorems in mathematics are undoubtedly ubiquitous.

5.3.4. Mathematical structure and scientific explanation: Prime numbers and cicada life cycles

Our last example of indispensably mathematical explanation of empirical phenomena is due to Baker (2005) and concerns the prime-numbered life cycles of the North-American *Magicicada*. Species of this genus emerge en masse every 13 or 17 years, depending on the species. The cicadas live for 2-3 weeks, mate, and die. The nymphs then remain in the ground for the duration of the period until their next scheduled emergence.

That the emergence of adults is synchronized among all members of a cicada species in a given area has an obvious explanation. Given the short lifespan of adults, fixed periodic emergence maximizes mating opportunities. What is not immediately obvious is why the cicadas have 13- and 17-year life cycles. Two hypotheses have been proposed, and each relies on the explanatory power of primeness.

The first proposed explanation is that long prime periods minimize intersection with periodic predators. Suppose that a nearby predator species had a 4-year cycle period. The emergence of 13-year cicadas would overlap with the predator species' emergence only once every 4 cycles. Contrast this with a 6-year cicada species, whose emergence would coincide with the predators' once every two cycles, and it is easy to see the advantage that higher prime-numbered cycle periods carry with them.

The second proposed explanation appeals to another possible application of this same number-theoretic property. Prime periods also minimize interaction between local cicada species with different cycle periods. This is desirable in order to prevent the creation of offspring with aberrant life cycles. Suppose there were two species of cicada that had 10- and 15-year cycle periods, respectively. If members of the two species were to mate with one another, they would produce offspring with either a 12- or 13-year life cycle. These offspring would miss the emergence of both of the original species and thus be deprived of the opportunity to mate and reproduce.

Both proposed explanations appeal to the irreducibly mathematical features of prime numbers. Prime periods are able to minimize undesirable intersection with other periodic species because prime numbers have only two divisors. Thus, having a prime-numbered cycle period bestows an evolutionary advantage that having a composite-numbered one does not. The hypotheses obtain their explanatory power by recourse to the relevant mathematical features of the biological system's structure.

As in the honeycomb case, the mathematical facts appealed to explain a *modal* physical fact. Facts about primality, when coupled with the biological law that having a life-cycle period that minimizes intersection with nearby periodic populations is evolutionarily advantageous, entail the likelihood that cicada populations living near other periodic species will evolve cycle periods that are prime. Note again that scientists *could have predicted* this fact given their knowledge of evolution and number theory. As in the honeycomb case, it seems to be merely a matter of historical contingency that the relevant mathematical knowledge led to explanation rather than to novel prediction.

5.4. The Problem of Applicability

Mathematical structures and relations are indispensable to our best scientific theories. Scientific prediction and explanation both work by unifying phenomena within more abstract theoretical structures, which are often mathematical. These mathematical structures capture *modal* not just *actual* features of the physical world. But even after we posit the mathematical entities required by the indispensability argument, a glaring question still remains: *Why* should mathematics be so applicable and indispensable to science?

As Colyvan (2001) argues, this is a question that all philosophies of mathematics face. Mathematical realism does not avoid it, nor does it answer it on its own. Thus, the conclusion of the indispensability argument – that we ought to be committed to mathematical entities – gets us only part of the way to the answer.

In the case of scientific realism, we do not solve the no-miracles problem by merely positing theoretical entities. We must also identify the relationship between the theoretical entities and the observable phenomena they were posited to explain. Ladyman and Ross put it as follows: "It is only on the assumption that the unobservable entities posited by realists *cause* the phenomena that they explain them. If unobservable entities merely happened to be around when certain phenomena were occurring, then their presence would not be explanatory" (74). It would be just as miraculous if observable phenomena were explained by appeal to theoretical entities with which they were merely correlated as if they were predicted by science but not explained at all.

While I agree that, in many cases, the relationship between unobservables and observables is a causal one, this is not true for every case. As we saw in the last chapter as well as in section 1 of this chapter, there are plenty of examples in which unobservable entities figure into *non*-causal explanation of observable phenomena. The Lorentz-invariance of spacetime, for instance, is not the sort of property to which we should ascribe causal powers, as it is a global symmetry of spacetime itself rather than a property instantiated at some location within spacetime. Yet, it plays an essential role in explaining why time dilation occurs. What is characteristic about all cases in which an unobservable property or entity explains an observable one is that there is a dependence-relation between explanans and explanandum.

It is clear that there must be some dependence relation between mathematical structures and modal physical structures. Facts about mathematical structures would not play an explanatory role in the empirical sciences if they "merely happened to be around." What then is the relationship between mathematical structure and the modal structure of the physical world? I suggest that it is *metaphysical dependence*. Facts about the modal properties of physical systems are *grounded* in facts about corresponding mathematical structures. Put another way, modal facts about physical systems hold *in virtue of* facts regarding their underlying mathematical structures.

What can be said about metaphysical dependence? First, it is a relation between facts or sets of facts.[50] It is asymmetric and irreflexive. Rosen (2010) notes that we must not assume the relation is a well-founded one. Since it is an open question as to whether there is a fundamental 'level' of reality, it is epistemically possible that there is an infinite chain of facts such that each fact is grounded in a subsequent fact or set of facts.

Some might object that the grounding relation is obscure or scholastic, that it can be no more than a loose heuristic. Rosen points out all the areas of discourse in which philosophers invoke such a relation and argues that, since we frequently appeal to the relation within philosophical discourse,[51] we have prima facie reason to believe that we understand the concept. The burden is therefore on the skeptic to point out exactly what is problematic with it.

Rosen thinks that at least one thing clearly follows from the extensive number of examples of the relation in philosophical literature – "We are often tempted to invoke the idioms of metaphysical dependence, which suggests that we often take ourselves to understand them" (112). This fact, he believes, shifts the burden from the relation's sympathizers to its skeptics. If the idioms of metaphysical dependence are unclear or problematic, we need some account of why this is so.

5.5. What is the explanatory value of metaphysical dependence?

[50] For the sake of this paper, let us take facts to be true propositions.
[51] He cites a number of examples from semantics, ethics, metaphysics, and political philosophy that express a thesis in terms of the grounding relation.

As I noted in the first chapter, a metaphysical theory is to be evaluated on the basis of its unifying power. The more a metaphysical theory can shed light on how seemingly disparate realms of science and scientific hypotheses relate to one another, the better it is. The strength of the metaphysical-dependence view lies in its ability to provide answers to a wide range of questions in the philosophy of science. I explore a few of them below.

5.5.1. What determines the modal structure of the physical world?

Scientific realists must be committed to an objective, mind-independent modal structure of the physical world in order to make sense of such things as causation, probability, equilibria, and laws of nature. But most available accounts of this modal structure are mysterious and unsatisfying. Merely asserting that modal structure as primitive, as Armstrong (1982), Maudlin (2007) and Ladyman and Ross (2007) do, fails to be illuminating. Primitivism about physical modality adds another type of necessity to the world without showing how it might relate to the other kinds of necessity with which we are familiar.

On the metaphysical-dependence view, we can understand nomological necessity in terms of mathematical necessity. The necessity of a law of nature, for instance, is explained by appeal to the mathematical structures that the relevant modal structure instantiates combined with the mathematical necessity of facts about the structure.

Of course, one might object that the metaphysical-dependence view has an additional primitive relation that primitivists about modal structure need not posit – namely, the relation of metaphysical dependence. Therefore, the metaphysical-dependence view is neither more illuminating nor more parsimonious than primitivism. But it must be noted that the metaphysical-dependence relation has a great deal of independent motivation outside of the goal of explaining the origin of modal physical structure. These include scientific motivations, such as accounting for non-causal explanation in science, as well as motivations from widely disparate areas within analytic philosophy. Since primitivism about modal physical structure cannot be similarly broadly applied, it cannot appeal to the same level of motivation.

5.5.2. Why is mathematics so applicable?

The applicability problem has received a great deal of attention in recent literature, yet no satisfactory solution has been offered. Some, such as Pincock (2004a) go so far as to deny that there is a problem. On his view, called the mapping account, "The existence of an appropriate mapping from a mathematical structure to a physical structure is sufficient to fully explain the particular application of the mathematical structure in question" (Bueno and Colyvan 2011). But we can still ask *why* the existence of some appropriate mapping between the mathematical and the physical makes the former applicable to the latter.

The deficiency of the mapping account is made clear by the fact that it leaves novel prediction from mathematical structure unexplained. It must be explained how the following is possible: "In the case of novel predictions, by invoking suitable empirical interpretations of mathematical theories, scientists can draw inferences about the empirical world that the original scientific theory wasn't constructed to make" (Bueno and French, 2).

Suppose that scientists had predicted that hive-bee honeycomb would be hexagonally structured before any honeycombs actually existed. Had it been the case that biologists knew of bees and their wax production, they could have predicted that bee populations that were stable over time would produce hexagonally structured honeycomb. How would the mapping account explain this? In this case, there is no *actual* empirical structure to which the relevant mathematical structure can be mapped. The relevant mapping would have to be from the mathematical structure to the *modal* structure of empirical system. So already we have moved beyond the resources of Pincock's account. And still there is the question of *why* this mathematical structure is applicable to the modal physical structure. This, of course, is analogous to the parallel question for scientific realists of *why* theoretical entities explain observable phenomena.

On the metaphysical-dependence view, the mystery of applicability is eliminated. We are able to make inferences from features about a certain mathematical structure to consequences about an empirical system just in case the modal structure of the empirical system metaphysically depends on that mathematical structure. When we cannot make such inferences, it is because no dependence relation holds between the structures.

5.5.3. Why are computer simulations so useful in the modeling and discovery of modal facts?

That scientists use computer models and simulations to gain useful insight into counterfactual scenarios is well known though hardly well understood. Evolutionary biologists use computer simulations to show what would happen in a given population if certain features of its make-up were changed. Thomas Schelling's (2006) famous model of segregation in Philadelphia showed that, in an integrated city consisting mainly of two racial groups, if everyone's preferences were at a mere 30% sameness threshold (meaning that if the make-up of a person's neighborhood became such that the percent of people who shared their ethnicity fell below 30, they would move), then the city would naturally become segregated in a shockingly short period of time.

How could it be that computer simulations can give us access to counterfactual truths? The metaphysical-dependence view offers a promising approach, particularly when paired with a structuralist account of mathematics. Given that the modality of the physical world comes from mathematical structure, and computations carry out functions that define the relations in mathematical structures, then the fact that scientific models and simulations can give us epistemic access to features of counterfactual scenarios seems to be a natural consequence.

5.6. Concluding remarks

There are clear parallels to be drawn between the no-miracles argument for scientific realism and the indispensability argument for realism about mathematical entities. For a theoretical entity to do explanatory work, it must bear some determination relation to the phenomenon it is supposed to explain. The metaphysical-dependence relation between modal physical structure and mathematical structure fulfills this requirement and sheds light on how it is possible to gain knowledge about the empirical world through mathematical inference.

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