SUPERPOSITION AND THE LIMITS OF DISPOSITIONALISM

A Dispositional Analysis of Quantum Mechanics

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Vienna, 02 June 2025

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ABSTRACT

This thesis examines whether the metaphysical framework of dispositionalism can accommodate the quantum phenomenon of superposition. Dispositionalism maintains that the laws of nature are grounded in the dispositional properties of physical systems—properties defined by their tendencies to manifest under certain conditions. While this stimulus–manifestation framework aligns well with classical mechanics, I argue that it falters in the quantum context, where states lack privileged representations and properties often exist in superposition. Attempts to rescue the dispositionalist account by appealing to probabilistic dispositions, or propensities, are unsuccessful: they either fail to explain the nature of quantum properties or their probabilistic structure. I close by proposing an alternative path forward, inspired by Aristotelian metaphysics.

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For my wife.

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CHAPTER 1: INTRODUCTION

Dispositionalism is the view that at least some properties are irreducibly dispositional. Within contemporary metaphysics of science, dispositional properties are increasingly viewed as one of the most promising candidates for providing a metaphysical explanation of the laws of nature. According to the dispositionalist account, the laws of nature identified by science describe and are grounded in the dispositional properties of physical objects. This suggests that any laws governing a system should be reducible to descriptions of the dispositional properties of the objects in that system. The reducibility of laws to dispositional properties provides a promising way to both test and refine dispositionalist theories: by evaluating their ability to accommodate scientific models. One of the key developments in science over the last century has been in quantum mechanics (QM). However, many of the most prominent presentations of dispositionalism have relied on examples from classical physics, rather than QM. In this thesis, I will evaluate the challenges associated with formulating a dispositionalist account of quantum mechanics, specifically examining whether dispositions can accommodate quantum superposition.

The primary motivation for adopting a dispositionalist metaphysics is the potential to explain the modal character of the laws of nature. Laws of nature describe regularities in the relations between properties, objects, or events, but not all regularities are considered laws because some of them hold accidentally. In contrast, laws seem to hold with some form of *necessity*. The dispositionalist accounts for this by grounding the necessity of the laws of nature in the essences of dispositional properties (Ellis 2002). Rather than treating laws as brute regularities or external governing principles, dispositionalism seeks to explain laws as emerging from the intrinsic properties of objects themselves. On this view, to have a property is to be disposed to behave a certain way under certain conditions, and it is this behavior that the law describes.

One critical benefit of a dispositional account of laws is that it explains laws as relations between properties, not as relations between facts. As Cartwright famously observes in *How the Laws of Physics Lie*, if laws of physics describe facts then they are never true, much less necessary. Laws describe ideal scenarios, where only a single causal factor is present, but such situations are at best only approximated, usually in a laboratory environment (Cartwright 1983, 55). However, if we regard laws as describing how powerful properties interact, then we can again regard laws as true. Laws describe the causal contributions properties make towards an outcome, though the outcome itself may depend on several other factors (Cartwright 1983, 61). Thus, laws describe how properties behave under ideal conditions because those are the conditions when no other causal factors are present.

As we have seen, both metaphysics and the philosophy of science give us good reasons to favor a dispositional account of laws. Moreover, additional motivation to adopt dispositionalism comes from quantum mechanics. As Heisenberg famously demonstrated, the properties of fundamental particles could not be exhaustively delineated. This constraint is not a practical limitation of our ability to measure, but an objective feature of the world. In his Gifford lectures, Heisenberg likened the objective probabilities which follow from his uncertainty principle to Aristotelian "potentia" (Heisenberg 2000). Modern dispositionalism draws heavily from Aristotle's theory of potentiality, providing another justification for understanding the laws of nature in terms of dispositions.

The advent of quantum mechanics led some philosophers—most notably Karl Popper and D. H. Mellor—to develop dispositional theories of probability. These "propensity theories" describe dispositional properties that manifest probabilistically (Popper 1959; Mellor 1971). At least in Popper's case, propensity theories were explicitly formulated to accommodate the probabilistic aspects of quantum mechanics, and most current dispositional theories have been content to adopt a propensity approach to probability (Mumford and Anjum 2010; Bird 2007).

The ubiquity of this approach has led to a remarkable lacuna in the dispositionalist literature. Despite insisting that dispositions ground fundamental laws, dispositionalists draw the preponderance of their scientific examples of dispositions from classical physics and chemistry. This has led many philosophers of science to accuse dispositionalists of being out of touch with current scientific theory and practice (French 2020).

This thesis has two parts. In the first, Chapters 2-3, I present a dispositionalist approach to classical physics. My project is providing a schema for grounding classical laws in dispositional properties, deriving much of my inspiration from Bird's (2007) work on the subject. Through this exercise, I examine the key conceptual resources that make dispositionalism successful in that domain. In the second, Chapters 4-5, I examine what I call the problem of quantum superposition. I then trace the roots of this problem to an absence of a privileged representation of the properties of the wave function and examine how this problem dogs the prominent, probabilistic approaches to dispositions championed by Karl Popper and D.H. Mellor. I close by proposing a way forward that may resolve some of the objections that I have raised.

CHAPTER 2: DISPOSITIONS AND LAWS OF NATURE

Before we can understand the challenges that quantum mechanics poses for dispositionalism, we must first understand what dispositions are and how they are typically applied to scientific phenomena. While the ways of understanding exactly what is meant by the term 'disposition' are myriad, there is general agreement that dispositions are properties characterized by their directedness towards a manifestation. Manifestations are typically regarded as events, and so a disposition can be plausibly understood as the tendency of an object to undergo a certain event in response to some stimulus. This stimulus-manifestation structure constitutes the typical way we conceptualize dispositions.

2.1 The Structure of Dispositional Properties

We regularly encounter dispositions in everyday life. One paradigmatic instance is that of fragility, which is the tendency for an object (say, a glass) to break when struck. However, dispositions also have applications in scientific contexts. These can include chemical properties such as solubility or acidity, but we will focus on dispositions' application in physical contexts. Most dispositional treatments of physics survey properties such as mass and charge (see, for instance, Bird 2007; Hüttemann 2009). These fundamental dispositions can then be described by the dynamical equations of physics such as Maxwell's equations or Newton's laws. In this thesis, I will focus primarily on mass, since it is most familiar and can be expressed in simple equations with few variables.

2.1.1 Dispositions and Potencies

Before proceeding, we should distinguish between individual dispositions and dispositional properties, sometimes called potencies or powers.[2] As we have seen, to ascribe a

[2] In this paper, I will use dispositional property, potency, and power interchangeably.

disposition to something is to say that it produces a certain manifestation in response to a given stimulus. However, possessing a single disposition may not exhaust the nature of the property responsible for that disposition.

To clarify this distinction, Brian Ellis uses the term 'dispositional property' to refer to any property that exhibits a dispositional causal structure across a range of conditions ((Ellis 2002, 76-77). Alexander Bird prefers the term 'potency,' though he has something similar in mind (Bird 2007, 44-45). On both accounts, these are properties whose essences are defined by how they tend to behave in certain circumstances. If the relevant stimuli vary, the manifestations may also vary. Now, a massive object has the disposition to fall if dropped and the disposition to move in a parabolic arc when thrown. We can treat these as distinct dispositions with different stimuli and manifestations. However, both types of motion can be explained by appealing to the same underlying property of mass as characterized by Newton's law of gravitation. The law of gravitation describes the dispositional character of the object, that is, given a certain stimulus condition, the law of gravity describes how the object will behave in virtue of its mass. Thus, it is dispositional properties—not individual dispositions—that ground the laws of nature. The above considerations suggest a very natural strategy for relating dispositions and the laws of nature: reduce both to dispositional properties.

2.1.2 Dispositional Properties: A Formal Characterization

We are now able to characterize the formal structure of the relationship generally taken by dispositionalism to hold between dispositions, potencies, and laws of nature. The standard account is formulated most clearly in (Bird 2007). There, Bird offers the standard conditional analysis of dispositions, where the disposition is characterized in terms of a counterfactual conditional:[3]

[3] This is conditional analysis is presented in (Bird 2007, 24).

(Eq. 2.1) $D_{(S,M)}x \leftrightarrow Sx\Box \rightarrow Mx$

This formalization states that an object has a disposition, D, iff when the object is exposed to stimulus condition, S, it results in the manifestation, M. Furthermore, Bird defines a potency (or dispositional property) as a property with a dispositional essence, such that:[4]

(Eq. 2.2) $\Box(Px \rightarrow D_{(S,M)}x)$

Equation 2.2 tells us that necessarily, if an object has the potency, P, then it has the disposition to M under conditions, S. From these two assumptions, Bird derives the following formula, which he takes as the basis for the reduction of laws:[5]

(Eq. 2.3) $\forall x((Px \ \& \ Sx) \rightarrow Mx)$

This states that for any object that has the property, P, under the stimulus conditions, S, that object will produce the manifestation, M. This is just what laws of nature tell us; they identify how an object with a certain property will behave under a given circumstance.

One more step remains; laws don't tell us what happens only under a given stimulus, but across a whole range of stimuli. Therefore, we need to generalize (Eq. 2.3) over the entire set of dispositions entailed by the potency, P. To do this, need to specify all the dispositions that are entailed by the potency in which we are interested. To do this, we will define a set of stimulus manifestation relations, I_P:

(Eq. 2.4) $I_P =_{def} \{(S_i,M_i) \text{ s.t. } \Box(Px \rightarrow D_{(Si,Mi)}x)\}$

Equation 2.4 allows us to formally capture how a potency not only entails a set of dispositions, but also specifies both the structure and scope of the laws associated with it. The directedness of the law towards a given outcome is explained by the fact that potencies entail particular dispositions. Moreover, because the relevant stimuli and manifestations are determined by the potency, I_P identifies the domain over which the law applies and constrains the mathematical

[4] Equation 2.2 is drawn from (Bird 2007, 45). He identifies it as (DE_P).
[5] For the proof, see (Bird 2007, 46).

form the law takes. In this way, Equation 2.4 reveals how potencies unify the manifold dispositions they entail, organizing them into a coherent explanatory structure.

Now that we specified the scope of the law of nature in terms of the potency, P, we can formulate an indexed version of Equation 2.3 so that it generalizes across all and only the dispositions entailed by P:

(Eq. 2.5) $\forall i \in I_P, \forall x((Px \ \& \ S_i x) \rightarrow M_i x)$

We thus have a generalized formula that tells us that for every stimulus-manifestation pair determined by P, and for every object, x, if x has the property, P, and undergoes a stimulus, S_i, it will produce the corresponding manifestation, M_i. This allows us to generalize the result of Equation 2.3 across all dispositions entailed by P.

Taken together, Equations 2.4 and 2.5 show that both the quantificational scope and the formal structure of the law are grounded in the nature of the potency, P. That is, P does not merely ground an isolated instance of a law, but determines the entire domain and logical form of the law by way of the structure of I_P. The goal of this formulation is to unify the law's domain, structure, and modal force in terms of the potency P, yielding a metaphysical reduction of the law to the dispositional property it describes.

It is important to note that while I have specified that P grounds a given law of nature, I have intentionally left the internal structure of P itself unspecified. This is because the aim here is to provide a general framework that captures how potencies relate to laws of nature in a way that is broadly acceptable to dispositionalists, rather than to defend a specific theory of how particular potencies function. For instance, all charged particles exert a force proportional to the inverse square of the distance between them; they have the same mathematical structure. While Equation 2.4 does not explain why all the relevant dispositions contained within the potency of charge have the structure they do, it affirms that the unity and structure of those dispositions are to be explained by reference to the potency. This allows us to identify the

metaphysical source of the law without committing to a specific mechanistic or structural theory of the potency itself.

2.2 Objections to the Dispositionalist Reduction of Laws

While the formal treatment developed above is compatible with a variety of theories about the nature of potencies, it draws heavily on Bird's (2007) framework and must therefore respond to prominent critiques of that view—particularly those advanced by Barbara Vetter.

2.2.1 Bird's Metaphysics and Vetter's Critique

A distinctive feature of Bird's metaphysics is his commitment to the fundamentality of "pure," single-track dispositions. In his view, potencies such as charge are not themselves fundamental properties, but conjunctive bundles of more basic single-track dispositions (Bird 2007, 22). These fundamental dispositions are characterized by a single stimulus-manifestation pair. In contrast, properties like mass and charge are "multi-track" dispositional properties, since they can manifest in different physical outcomes depending on the stimulus conditions. On this view, a potency is a complex disposition rather than a separate metaphysical category. Bird's atomistic view of potencies thus treats even the most basic physical properties as metaphysically dependent on a set of simple, atomic dispositions, each governing a distinct aspect of the property's behavior.

Vetter (2015; 2012) offers a compelling critique of this picture, arguing that laws of nature cannot be adequately characterized by isolated single-track dispositions. Her concern is that single-track dispositions do not suffice to explain the laws of nature, because a law does not describe what occurs under a single circumstance, but under a host of initial conditions. If each pure disposition governs only a narrow slice of behavior, then the laws associated with a potency become a scattered patchwork, lacking the unity and systematicity we expect of genuine laws of nature. As Vetter says, it "leave(s) entirely unexplained and inexplicable the

much more striking regularity that holds between those more specific regularities of behaviour" (Vetter 2015, 58). Furthermore, if a potency is simply a conjunction of dispositions, as Bird believes, then the nature of the potency is grounded in the conjuncts themselves. But we have already established that dispositions are unable to themselves to ground the laws of nature. Since grounding is transitive, if P can explain the laws of nature, then what grounds P must be able to explain the laws of nature. Dispositions cannot ground laws. Therefore, potencies also cannot ground laws (Vetter 2012, 12).

If potencies are merely conjunctive bundles of single-track dispositions, then we lose the ability to explain why those particular dispositions cohere into a unified property. The structure of the potency becomes a brute conjunction, leaving the explanatory role of the potency—and of the laws it grounds—undermined. This would require us to re-read Equation 2.3. Because on Bird's view, $P =_{def} (D_1 \ \& \ D_2 \ \& \ D_3 \ldots)$, we must now understand it as saying that for any object which has a conjunction of dispositions of which $D_{(S,M)}$ is one of the conjuncts, under the stimulus conditions, S, that object will produce the manifestation, M. But this strategy fails to reduce the laws of nature.

Even if we accept the indexed law schema described by Equations 2.4 and 2.5, Bird's model still fails to account for the structural unity of the various single-track dispositions. On his view, membership in P must remain a brute fact, so there remains no explanation for why these diverse stimulus-manifestation links jointly define a single, law-governing property. Thus, we are left with a fragmented metaphysics that cannot explain the scope or structure of laws without appealing to unexplained regularities among the conjuncts.

2.2.2 Preserving the Reduction of the Laws of Nature in Terms of Counterfactuals

Vetter takes this failure to motivate the conclusion that properties are more fundamental than the single-track dispositions used to define them. As I mentioned in Section 2.1.2, I am

sympathetic to this conclusion. However, I disagree with her further claim that this undermines the counterfactual characterization of dispositional properties (Vetter 2012, 14). Abandoning counterfactuals would sever the explanatory connection between potencies and laws altogether, a move that undermines the very project of dispositional essentialism (French 2020, 25-26).

Vetter bases her rejection of counterfactuals on the claim that they fail to explain the correlation between the suite of properties that together constitute the stimulus condition and that this broader regularity is what truly needs explanation. What constitutes a law of nature is the continuous and mathematically structured correlations between properties. In these cases, the counterfactual form becomes explanatorily inert, unable to account for the systematic variation that the law encodes (Vetter 2012, 14). On the contrary, *both* the correlation between properties and the counterfactual condition are necessary to give a full account of the laws of nature. The dispositionalist can agree that the mathematical regularities that hold between properties are essential features of the laws of nature, but this does not exclude the role of counterfactuals. There are many mathematical regularities between properties that we don't consider to be laws of nature; laws require something more. They must hold with some form of modal force or necessity, and it is this modal force that the counterfactual is meant to explain. For a statement to be a law, it must express both a regularity between properties, and that regularity must have some modal force.

Once we drop Bird's commitment to the metaphysical priority of single-track dispositional properties, we can appeal to potencies to fill both explanatory roles. Potencies account for the structured mathematical relationships between properties, and they provide the modal force that marks these relationships as lawlike. While Vetter is right to emphasize that the laws of nature express continuous and mathematically precise correlations, identifying such regularities in practice and understanding their modal significance requires an underlying counterfactual structure. This is evident in the scientific method. When scientists test for laws,

they vary one parameter while holding others constant in order to determine whether and how that variable affects the outcome. This process presupposes counterfactual reasoning: if the property were different, the effect would differ in some specific way. In this sense, counterfactuals are not dispensable add-ons to mathematical structure. Rather, they are what make that structure explanatory. A law must do more than describe a pattern; it must tell us how the world would behave under different conditions. Therefore, while laws of nature involve more than just their modality, it is the counterfactual structure that captures the modal dimension that distinguishes laws from mere regularities.

My suggestion is that potencies do not merely collect dispositions but structure the space of possible manifestations. Critically, as we saw above, this additional mathematical structure does not undermine the dispositional essence of potencies. Rather the structure *itself* has a counterfactual character. If we treat potencies, rather than dispositions, as fundamental, then Equation 2.4 tells us which properties are relevant to produce a given manifestation. We can think of the set of stimulus-manifestation pairs as forming a "dispositional space," where each dimension corresponds to a property that contributes to the stimulus condition. Each point in this space represents an individual disposition, and the structure and dimensionality of the space are determined by the nature of the potency. This perspective allows us to retain a counterfactual analysis while grounding the law in a unified potency—even if the internal workings of that potency remain underdefined.

While I leave the internal structure of potencies underdefined, their metaphysical role is not merely aggregative, but organizational: potencies impose modal and structural constraints on how their constituent dispositions relate. Moreover, *pace* Vetter, the modality at work in the explanation of lawlike regularities is still most plausibly understood in counterfactual terms (2012, 14). While the viability of this view ultimately turns on how we characterize the nature of dispositional properties, I hope to have shown that Vetter's objection to Bird's view may be

resolved without rejecting the counterfactual structure of dispositional properties. In the following section, I will apply the structure I have presented here the laws of nature as they relate to mass, to show the viability of this approach as it relates to classical physics.

CHAPTER 3: DISPOSITIONS IN CLASSICAL PHYSICS

To ground a law of nature in a dispositional property, the dispositionalist needs merely to assign each component of a given law of nature a place within the formal structure of Equation 2.5. I will use the example of mass as a paradigm case.

3.1 Mass as a Dispositional Property

3.1.1 The Dispositional Analysis of $F = ma$

Newton's second law expresses the basic formula for mass, $F = ma$. In this case, each variable, force, mass, and acceleration, slots nicely into one of the predicates included in the formalism of dispositions. Within this dispositional framework, we will regard mass as our dispositional property, which we will represent using P_m. The stimulus condition is the net force on the object, F, and the manifestation is the acceleration under that force, a. We can define the relevant stimulus manifestation pairs as I_m as follows:

(Eq. 3.1) $$I_m =_{\text{def}} \{(F_i, a_i) \text{ s.t. } \Box(P_m x \rightarrow D_{(Fi,ai)} x)\}$$

From here, we can express the law in terms of the dispositional property:

(Eq. 3.2) $$\forall i \in I_m, \forall x((P_m x \,\&\, F_i x) \rightarrow a_i x)$$

This formulation states that for any object x, if it has given mass and is subject to a given force, F_i, then it will accelerate at the corresponding rate, a_i. In this way, Newton's law is understood as a generalization over the set of dispositions entailed by the mass of the object. Thus, the law reflects the structure of the potency itself rather straightforwardly.

One might object that Equation 3.2 does not ground Newton's second law, but merely one instance of that law, since it only holds for a single mass, while Newton's law holds for masses generally. This is a fair criticism, but the situation is easily remedied by treating P_m as the determinate of the more general determinable, mass. Thus, any object having the determinable property of having mass is grounded in having the determinate property, P_m.

Likewise, the tendency of all massive objects to obey the general formula, $F = ma$, is grounded in their having some determinate property for which Equation 3.2 holds.

It is also important to address another possible concern. That is, in using Newton's second law rather than, for example, the law of gravitation, I am stating not a dispositional property, but rather merely a definition for mass in terms of force and acceleration. Indeed, is not the entire thing just a little circular? One might argue that to accelerate a given mass, m, by a is *just what it is* to exert the corresponding force, F. If this is so, in making F the stimulus condition for a, have I not just defined the potency 'mass' as "what manifests a when it is disposed to manifest a"?

There are two things to keep in mind when addressing this critique. First, the interdefinability of dispositions is quite common, indeed, dispositions usually come in pairs.[6] While the complementarity of dispositions certainly raises philosophical questions (For discussion of this, see Williams 2010), it is in no way unique to my formulation, nor is it a consequence of it. Second, characterizing mass and force as I have done above does not preclude supplementary accounts of either property. In fact, since both mass and force figure in many more laws than Newton's second, it is evident that (NL) is not completely informative. Nevertheless, while incomplete (NL) does play a central role in characterizing mass, which I will briefly elaborate on below.

3.1.2 The Dispositional Analysis of Newton's Law of Gravitation

Let's look at another law describing mass: Newton's Law of Universal Gravitation, which states:

(Eq. 3.3) $$F = G\frac{m_1 m_2}{r^2}$$

[6] See, e.g., table salt's solubility and water's disposition to dissolve polar solutes.

The most natural dispositional reduction of *this* law is to treat the force, *F*, as the manifestation. The fact that we treat *F* as the stimulus in Equation 3.2 and the manifestation here should cause us no great alarm, many dispositionalist theories allow for the manifestation of one disposition to be a further disposition or stimulus condition. While this has led to objections such as the infamous "always packing" argument, as Molnar observes it isn't clear that any of the regress objections proposed are vicious (Molnar 2003, 174). Moreover, it is critical to note here that the *F* in Newton's Law of Gravitation does not stand in the same relation to a given massive object as the force described in Newton's second law. In that law, *F* represents the force exerted *on* an object, whereas in the Law of Gravity, *F* refers to the force exerted *by* a given body on another.[7] Therefore, I think we are free to treat *F* as the manifestation here. Let us begin as before by defining the set over which the law holds:

(Eq. 3.4) $I_G =_{def} \{(S_i = m_{2i} \text{ at distance } r_i, F_i) \mid \Box(P_{m1}x \rightarrow D_{(Si,Fi)}x)\}$

And reducing the law as follows:

(Eq. 3.5) $\forall i \in I_G, \forall x((P_{m1}x \,\&\, S_i x) \rightarrow F_i x)$

We can summarize the content of Equations 3.4 and 3.5 as the statement for any object x, If x has the mass m_1, and it exists in a configuration such that another object with mass m_{2i} is present at distance *r*, x will exert a gravitational force, F_i.

Unlike $F = ma$, the Law of Gravitation features multiple properties that contribute to the stimulus condition. Again, we avoid Vetter's critique by grounding the structure of S_i in the nature of the potency P_{m1} itself. That is, it is the dispositional profile of mass that explains why changes in configuration systematically vary the resulting force. Thus, I_G is not a brute enumeration of force-producing conditions, but a unified, modal space structured by the nature

[7] This statement may be open to some debate. The Law of Gravity is symmetrical, so the force exerted by each mass on the other will be the same, which makes the selection of which force you are referring to somewhat arbitrary. However, within our dispositional account, it would be silly to identify a manifestation of a potency of object, a, to be the force some object, b, exerts on it. Therefore, we can safely say that the force described by Newton's second law does not stand in the same relation to an object as the force described by Newton's Law of Gravitation.

of gravitational potency. Thus, we can see that our reduction schema works for both when stimulus conditions are concretely given or referred to more abstractly.

3.2 Accounting for Common Features of Dispositions

So far, we have presented an example of how to apply our dispositional scheme to laws of nature in classical physics. However, before advancing to QM, it may be fruitful to examine how common features of dispositional theories figure into our own. To that end, we will briefly explore how some common dispositional concepts apply to our formulation.

3.2.1 Multi-Track Dispositions

As we saw above, multi-track dispositions are those dispositional properties that feature multiple stimulus-manifestation pairs. In Section 2.2, we argued against Bird and with Vetter that multi-track dispositions such as mass and charge seem to be more fundamental than the individual, atomic dispositions that they entail. However, this position requires us to provide some answer to the question of how potencies are individuated, since, as Vetter observed, they cannot be individuated solely by the individual dispositions they entail (Vetter 2015, 61). The most natural solution, and the one that we have tacitly adopted heretofore, is to individuate potencies based on their shared mathematical structure. This allows us to provide an un-gerrymandered characterization of potencies. That is, potencies are not just unified by the collection of their effects, but by the structural relationships that hold among those effects. This suggests that the mathematical structure of potencies is responsible for individuating them.

This is a clean solution, but our treatment of mass in Section 3.1 raises some questions. Mass figures in multiple laws of nature. These laws have distinct mathematical structures, leading to distinct dispositional analyses of each law in Equations 3.2 and 3.5. This raises an important question: are Equations 3.2 and 3.5 describing the same dispositional property? How we answer this question will have a profound impact on how we individuate dispositions.

There are two options. One is to say that Equations 3.2 and 3.5 describe two distinct dispositional properties. However, if we take this route, we are left with an unexplained connection between these two properties. All massive objects appear to necessarily have both properties—whenever one is present, so is the other. This creates an explanatory gap that cannot be bridged from within the dispositional framework itself. The second, and more promising, option is to treat these formulations as partial expressions of a more general potency: one whose full dispositional profile is multi-dimensional and reflected in the mathematical structures of the laws themselves. Each law isolates aspects of this more general potency. On this view, mass does not merely yield either acceleration or gravitational attraction—it does both, and it does so as part of a unified dispositional profile. Just as the stimulus conditions can be multi-dimensional, so too can the manifestations.

The second option aligns mass the dispositional property with mass as it is mathematically characterized. For the dispositionalist attempting to provide a reductive account of the laws of nature, this seems like the right result. On their account, the laws of nature all describe dispositional properties. If one equation describing the mass of an object refers to a different dispositional property than another equation referring to the mass of the same object, then that reduction seems to have failed.

While the structure sketched above may help provide a unified explanation for the laws of nature, we should not seek such unification for all multi-track dispositions. While mathematical structure is critical for specifying the dispositional properties within physics, this need not be the only way to group dispositional properties. For instance, fragility is typically regarded as a multi-track disposition because there are a number of stimulus conditions that result in the manifestation of fragility. In this case, there is no mathematical structure that specifies fragility. Rather, it seems to refer to a set of similar dispositions shared across objects with different potencies (such as a glass and a ceramic vase). Identity conditions are less

concerning in this case because there is no need to ground a law of nature that fragile things break. Some of our dispositional language groups dispositions based on features of the world that are interesting to us in everyday life, such as fragility, and some, such as the laws of physics, attempt to describe the structure of reality. Because potencies such as mass play a more important metaphysical role, they require a more meticulous characterization than more colloquial dispositions.

3.2.2 *Ceteris Paribus* Conditions

In the section above, we discussed how the laws of nature are partial characterizations of more complex dispositional properties. This approach not only clarifies how we might unify complex dispositional properties but also offers a principled way to interpret *ceteris paribus* clauses—those ubiquitous but often vague conditions that accompany many laws of nature.

We will begin with the law of gravitation because it is often a favored example in dispositionalist accounts. This is due to the stimulus conditions being explicitly defined in terms of the discernable properties of an object, such as mass and position.[8] From this starting point, the common strategy is to deduce phenomena such as the elliptical motion of the planets. This gives us a paradigm case of the concrete circumstances of an object disposing that object to a specific behavior (Hüttemann 2009). However, the move from Newton's law to the description of the planet's orbit is too quick. As we showed, the manifestation resulting from P_{m1} if we take it as written (which we should!) is the gravitational force one body exerts on another. However, in order to get the dispositional statement that celestial bodies tend to orbit each other in elliptical orbits, we need two further statements. We first need to be able to convert our statement about gravitational force to a statement about acceleration. This should sound familiar; it's just Newton's Second Law! We must also specify the relevant circumstances in

[8] This is in contrast to the more abstract stimulus condition of force given in our analysis of $F = ma$.

which the laws apply, that is, we must provide a *ceteris paribus* condition. We will now briefly turn to how our formulation of dispositions may help in specifying those conditions. Let us now consider how our formulation of dispositions helps clarify such conditions.

On my account, these *ceteris paribus* conditions can be precisely stated in dispositional terms. When we invoke *ceteris paribus* conditions, we restrict the possible situations in which the behavior predicted by the law will occur (Hüttemann 2009). On what basis do we do this? Cartwright argues that in order to specify *ceteris paribus* conditions, we must already have an idea of what other factors are causally relevant (Cartwright 1979). But for the dispositionalist, the causally relevant factors are just other dispositions. Therefore, we should be able to specify *ceteris paribus* conditions purely in terms of dispositional properties. I will show below that my reduction of laws allows just that.

To specify the *ceteris paribus* conditions for planetary motion, we need to isolate a single causal interaction described by Newton's Law of Gravitation. Conveniently, this can be done by appealing to Newton's Second Law. Specifically, the Law of Gravitation predicts the behavior of the planets when the two massive objects in question are the only source of force on each other. But this is just a certain subset of I_m such that the manifestation in Equation 3.5 is the sole contributor to the stimulus condition in 3.2. Put differently, the manifestation described by Equation 3.5 must be the stimulus condition in Equation: $F\text{i}\mathrm{X}_{(Im)} = F\text{i}\mathrm{X}_{(\mathrm{IG})}$. This formulation allows us to understand *ceteris paribus* conditions as the selection of a subset of possible stimulus conditions. This is done by restricting the number of sources of the stimulus, as above, or by restricting the type of properties that are part of the stimulus that are varied.

This framework helps clarify the nature of *ceteris paribus* conditions. On the view developed here, laws that hold *ceteris paribus* are partial descriptions of dispositional properties, where certain aspects of the full stimulus conditions are held constant. These conditions are not external idealizations but reflect the internal structure of the disposition itself.

When a law holds *ceteris paribus*, it isolates a particular aspect of a potency's behavior by treating other relevant stimuli for that same potency as fixed or inactive. In this way, *ceteris paribus* clauses mark which parts of the full dispositional structure are being bracketed in order to highlight the contribution of a specific stimulus–manifestation link.

So, rather than undermining the dispositional analysis, *ceteris paribus* conditions presuppose the multidimensional structure of the disposition. This sharply contrasts with Bird's treatment of such conditions. On his view, *ceteris paribus* clauses do not apply at the fundamental level because the dispositions themselves are simple and isolated. On my account, by contrast, these conditions do not apply fundamentally because a complete specification of the stimulus condition already exhausts all the factors relevant to the manifestation. A *ceteris paribus* qualification indicates that the dispositional profile of the potency being described is incomplete. While this treatment of *ceteris paribus* conditions may be unorthodox, I believe it better reflects how science formulates laws of nature: by abstracting from the general behavior of a property to describe a single regularity.

3.2.3 Pleiotropy, Polygenicity, and Vector Addition

In the preceding section, we offered a characterization of ceteris paribus conditions and attempted to explain them in terms of a restriction on the stimulus conditions of a theoretically complete dispositional characterization of scientific properties such as mass. Because our analysis has committed us to the position that many properties collectively constitute the stimulus conditions of dispositional properties, we must determine how these conditions are unified into a single input. As Equation 2.4 affirms, the ordering of parts of the stimulus into a whole is attributable to the structure of the potency in question, but we have yet to say anything about how this may occur. One promising avenue to explore is to examine how science combines physical quantities. In classical mechanics, this often takes the form of vector addition.

A vector is a mathematical object characterized by both a magnitude and a direction. In physics, vectors are commonly used to represent quantities such as force, velocity, and acceleration because these quantities have both size and directional components. When multiple vectors act on an object, they can be combined using vector addition to produce a single "resultant" vector that reflects the net effect. This mathematical feature makes vectors especially useful for modeling how physical properties interact within a dispositional framework.

There is also a conceptual resonance worth noting. Just as a vector is defined by its magnitude and direction, a disposition is typically directed toward a specific type of manifestation and can vary in intensity. This analogy has been explored by Mumford and Anjum (2010; 2011), who suggest that dispositions may be fruitfully modeled as vector-like entities.[9] However, rather than pursuing a full-blown vector model of dispositions, I will focus on how vectors help reveal the structural commitments of our dispositional framework. Understanding this connection will be critical to assessing how well such a framework accommodates the mathematical structures of quantum theory.

Let us use our treatment of $F = ma$ as our working example. For the potency, P_m, the stimulus condition for all dispositions entailed by P_m are forces, meaning each of those stimuli can be represented as vectors within classical three-dimensional space. Likewise, all manifestations of the dispositions entailed by P_m are accelerations, which are also vectors in that same space. Furthermore, the dispositions entailed by the potency transform a stimulus into a manifestation. We can therefore treat P_m as a function for which the input is a force vector and the output is an acceleration vector.

[9] For instance, something can be more or less fragile. One can understand this as having a stronger or weaker directedness towards the shattering just as vectors can have a greater or smaller component in a dimension of vector space. This is the view defended by Mumford and Anjum (2010).

To illustrate, let's take an example adapted from (Molnar 2003, 195-6). Two horses pull a barge down a canal. Each horse walks on either bank and pulls against a slight current. We can model the forces exerted on the barge using vectors, each creating an impulse for it to go in a certain direction (Figure 1). How do we decide how the barge moves? The answer is that we add the vectors, together to produce a single resulting vector, which allows us to predict the acceleration of the barge at that moment.

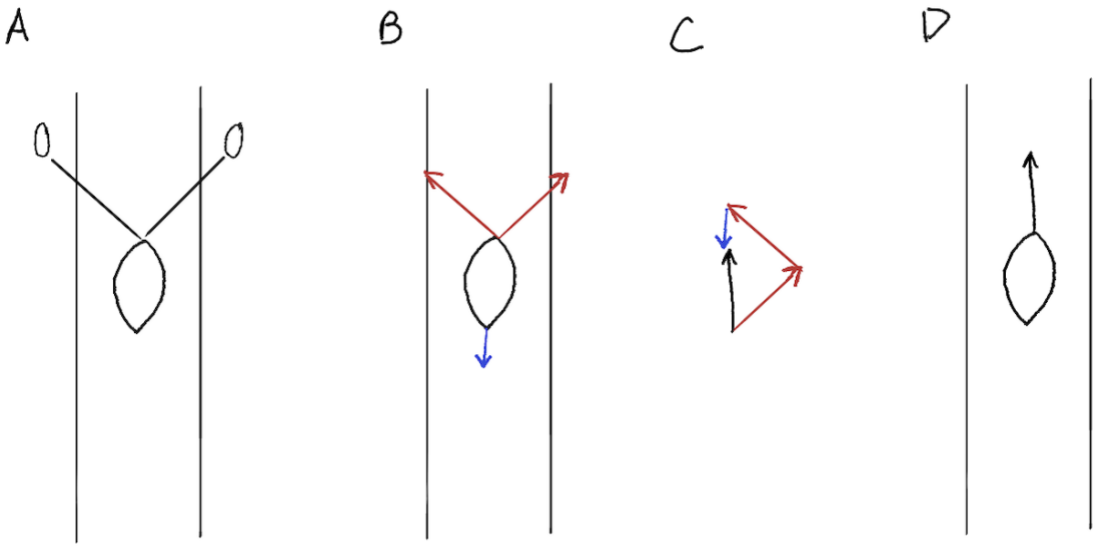

Figure 1

But what exactly is being manifested here? Do each of the horses activate their own dispositions, or does only a single, unified disposition manifest in the barge? As Molnar points out, John Stuart Mill might be inclined to affirm the former: "In this important class of cases of causation, one cause never, properly speaking, defeats or frustrates another; both have their full effect" (Mill 1893, as cited in Molnar 2003, 196). Only one acceleration occurs. If we were to frame this in terms of the activation of three dispositional properties, none would be manifested because the accelerations that are the manifestations of each force taken in isolation do not occur. Thus, we must add the vectors in order to properly identify the activated disposition in the barge case if Equation 3.2 is to hold.

However, the objection might arise that we have traded the unity of one stimulus-manifestation pair for another. If we look at the horse, it has a disposition to move the barge in the direction that it is pulling it, but this outcome never manifests. Thus, we have traded the proper manifestation of the barge's disposition for the horse's. This objection mistakes the total state of the system for the manifestation of a part of that system. In reality, the horse's disposition *is manifested*, it just isn't the manifestation to move the boat. Rather, just as in the case of gravitation, the horse has the disposition to exert a force on the boat, and this disposition is clearly manifested. Indeed, it is part of the stimulus that determines the manifestation of the boat.

This shows us that the potencies involved are both polygenic and pleiotropic: multiple causes contribute to a manifestation, and a single manifestation reflects the influence of more than one contributing cause (Molnar 2003, 194-195). The manifestation of the potency of the barge to accelerate is polygenic because it results from the combined contributions of several distinct force vectors, each associated with different objects. Likewise, in pleiotropy, the horses' dispositions to exert force are manifested in a shared effect: the barge's motion. In both cases, identifying the correct stimulus and manifestation depends on our ability to predictably combine the contributing forces. Thus, the mathematical structure of vector addition mirrors the causal architecture of potencies: they integrate multiple contributing stimuli into a single, determinate manifestation. On this model, potencies function as causal nodes that receive structured sets of inputs and yield unified outputs. Their structural role in combining stimuli through operations like vector addition explains how complex causal profiles generate a single, determinate effect.

However, this framework also introduces a serious challenge: superposition. Vectors can always be added together within the same vector space—but crucially, the reverse is also true: any vector can be decomposed into infinitely many combinations of component vectors (Figure 2). As the figure illustrates, a vector can be expressed as the sum of various component

vectors, each weighted by a projection coefficient. This is accomplished by summing the products of each component vector, v_i, and its projection coefficient, c_i, which indicates how much that component contributes to the overall direction and magnitude of the resultant vector. The projection coefficient identifies to what degree a component vector contributes to the resultant. Importantly, any vector can be treated as a component of any other by identifying its projection coefficient. This fact introduces a representational ambiguity. The very operation that allows us to treat the manifestation as a function of many inputs also allows us to reframe a single input as if it resulted from many components. This dual feature of vectors has the potential to undermine our ability to uniquely identify the stimulus or manifestation associated with a given dispositional property.

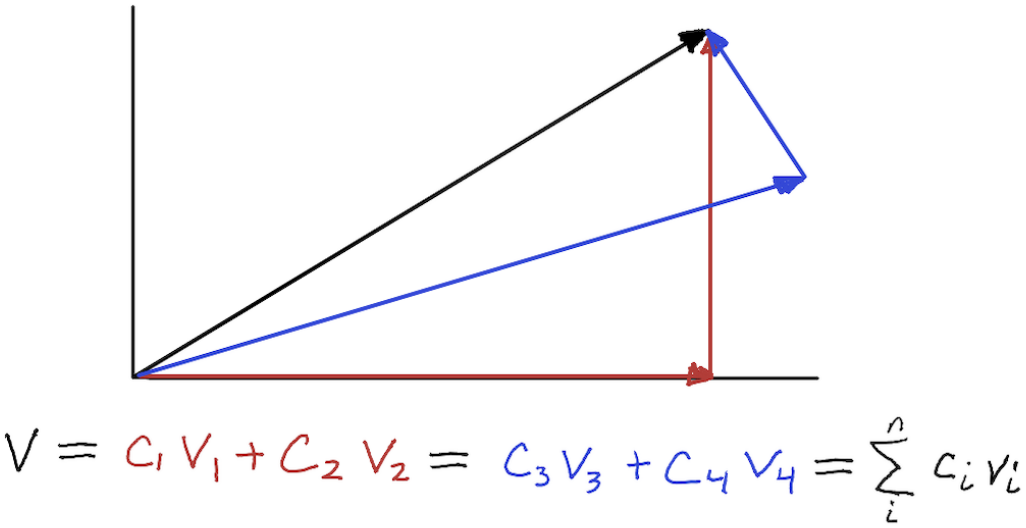

Figure 2

Superposition suggests that for the dispositional account to remain coherent, we must identify a privileged representation of the system's state, one that corresponds to the actual stimulus and manifestation relevant to the potency. In classical mechanics, this is unproblematic. Each property has a definite value, so even though some force F may be

decomposable into $F_1 + F_2 + F_3\ldots$, the net force F has a privileged standing as the actual stimulus. This is what allows our dispositional analysis to remain coherent and explanatory.

3.3 Taking Stock

The end of this chapter represents a turning point in this thesis. So, before proceeding, it will be profitable to pause and take stock of where we are. To this point, I have presented an account of dispositions that relies heavily on the formalization developed by Bird, but with a very different metaphysics underneath. Rather than treating single-track dispositions as fundamental, I have embraced the fundamentality of multi-track dispositional properties, especially those properties represented by variables within fundamental physical equations. Furthermore, I have argued that while these properties cannot be reducible to a conjunction of dispositions, they retain a modal character that is best represented counterfactually.

In this chapter, I have applied the formalism presented in Chapter Two to the laws of classical physics, grounding them in the dispositional properties they describe. For such a reduction to be successful, we must account for all aspects of the laws of nature in terms of dispositional properties. The primary implications of this for the dispositional theory I have sketched above are that physical quantities such as mass are taken to be fundamental, multi-track dispositional properties and that individual laws of nature describe aspects of those properties. This requires the potencies themselves to structure the stimulus conditions into a single input, to preserve their counterfactual structure. I have argued that one-way potencies do this is by vector addition. However, because vectors can be arbitrarily decomposed, this reading is underwritten by the assumption that the system admits a privileged representation, such as the net force in classical mechanics. These aspects are key to ensuring that our reduction of the laws of nature to dispositional properties is complete.

To this point, we have constructed an edifice characterizing dispositional properties generally and in classical physics in particular. The rest of this paper shall be spent dismantling

this edifice. In the following Chapter, I will present and analyze some problems posed for dispositionalism by quantum mechanics (QM). Just as in classical physics, QM relies on vectors to model aspects of quantum theory. However, unlike classical physics, vectors in quantum mechanics lack a privileged representation. This creates what I will call the problem of quantum superposition for the dispositional analysis of quantum states.

Typical discussions of the relation between dispositionalism and QM have focused on how dispositions can accommodate the probabilistic nature of quantum phenomena. They do this by positing probabilistic dispositions: propensities. In Chapter 5, I will discuss two prominent propensity theories: those of Karl Popper and D.H. Mellor, and show that neither can provide a complete (and correct) explanation of the quantum formalism in terms of propensities. I will close this thesis by briefly discussing alternative strategies that dispositionalists might turn to.

CHAPTER 4: THE QUANTUM CHALLENGE TO DISPOSITIONALISM

In the last section, we offered a summary of how properties in classical mechanics can be modeled powers. In what follows, we will explore the conceptual revolution that occurred with quantum mechanics and the novel challenges it presents for dispositionalism.

4.1 The Classical–Quantum Divide: A Conceptual Overview

4.1.1 The Distinction Between Waves and Particles in Classical Physics

One of the most significant conceptual developments in modern physics is the advent of quantum mechanics. Among its most surprising results is what is often called wave-particle duality: the idea that quantum systems exhibit both wave-like and particle-like properties. This result is particularly striking because classical physics draws a sharp distinction between the two. On the classical view, particles are localized material entities that occupy a determinate position in space and possess well-defined properties. Waves, by contrast, are typically understood as extended disturbances in a medium or field, and their properties, such as amplitude and wavelength, vary across space and time.

To this point, our discussion of dispositions has focused on the dispositions of objects, and more specifically, of objects understood as particles. However, there is nothing in the dispositionalist framework that restricts it to particles alone. A dispositional analysis of fields is both possible and, as we have seen, in some respects already implicit in the classical case. For example, our treatment of Newton's Law of Universal Gravitation described the disposition of one object to exert a force on another at any point in space. But this is just to describe the gravitational field produced by that object. Thus, for the dispositionalist, force fields just describe the dispositions of an object to manifest a force across space. The value of the field at a given point is equal to the sum of all the fields present at that point, just as we have seen with

more conventional forces, such as those exerted on the barge in Figure 1. Waves, in turn, may be understood as localized excitations of such fields. Just as a pebble dropped in a still pond creates ripples that propagate outward, a field can exhibit wave-like behavior when it is disturbed.

For the dispositionalists adhering to classical mechanics, waves can be understood in terms of the dispositions of particles or systems of particles to produce certain effects under specific conditions. The classical world admits this kind of explanation of fields in terms of the dispositions of the objects that generate them, and the behaviors of systems are modeled using definite properties and privileged representations. It is against this conceptual background that the developments of quantum mechanics must be understood.

4.1.2 The Development of QM, and the Conceptual Break with Classical Physics

This relatively tidy framework of classical mechanics began to unravel in the early 20th century. To account for certain empirical anomalies such as blackbody radiation and the photoelectric effect, Max Planck and Albert Einstein proposed that light, which had been successfully modeled as a wave, also exhibited particulate behavior. That is, light appeared to come in discrete quantities, or "quanta." These observations suggested that some phenomena traditionally modeled as waves also had particle-like features. Louis de Broglie then offered the natural converse hypothesis: if waves can behave like particles, then perhaps particles—such as electrons—can also exhibit wave-like properties, such as wavelength or interference. This was later confirmed experimentally in the famous double-slit experiment, where electrons produced an interference pattern, even when fired one at a time. The implication is clear: matter at the quantum level behaves like a wave.

This insight was incorporated into the formalism of quantum mechanics through the Schrödinger equation. Rather than describing the evolution of a particle with definite position

and momentum, Schrödinger's equation treats quantum systems as wave functions—mathematical entities that evolve continuously over time and space. As we will see, these wave functions can be described as superpositions of states the particle could be in.

Here, however, a difficulty arises. Although the wave function evolves deterministically according to the Schrödinger equation, measurements of quantum systems do not reflect this continuous evolution. When a measurement is performed (e.g., of a particle's position or momentum), the system does not display a superposition of outcomes. Rather, it yields a single, definite result. The standard interpretation of this phenomenon is that the wave function "collapses" upon measurement: the system instantaneously transitions from a superposition of possible values to a single actual value, with the probability of each outcome given by the square of its corresponding amplitude in the wave function.

This probabilistic character of quantum mechanics marks a departure from the deterministic structure of classical physics. Importantly, the probabilities involved are not typically understood as reflecting ignorance. Rather, they appear to be objective features of the system, built into its very structure. This creates a potential challenge for a dispositional account of properties. If dispositions are directed toward the manifestation of specific effects under specific conditions, then it is not immediately clear how to reconcile this with the notion that a quantum system is directed toward a range of outcomes, each with a different probability of occurring.

A related difficulty arises from the Heisenberg uncertainty principle. Heisenberg realized that there was a limit on how precisely we can define the values of certain pairs of observables. For instance, the more precisely a particle's position is known, the less precisely its momentum can be specified. This limitation is not due to observational error or technological inadequacy but rather is a structural feature of the theory itself. The state of a particle as described by wave function does not encode determinate values for all observable properties at

once. Instead, which observables have well-defined values depends on how the system is prepared and measured.

This presents a significant reversal of the classical picture. In classical mechanics, one typically begins with the properties of a system—its mass, position, momentum, and so on—and uses those to describe its state. In quantum mechanics, one begins with the state itself, encoded in the wave function, and derives the system's properties from it, often only in probabilistic terms. This presents a significant challenge for the dispositionalist seeking to ground the laws governing the behavior of particles in the properties they possess. The state of the system is no longer fixed by its properties. Instead, the properties appear to depend on the system's state—and in some cases, on how the system is measured.

These features of quantum mechanics pose a challenge for the dispositionalist framework developed in previous chapters. If dispositions are to remain viable in this context, we need a way to characterize them that reflects the distinctive conceptual structure of quantum theory. Of particular concern is that quantum mechanics does not admit a privileged representation of a system's properties, as classical mechanics does. In what follows, I turn to the formal structure of quantum theory to clarify how these challenges arise and to assess whether a dispositional treatment remains tenable.

4.2 The Structure of the Wave Function

4.2.1 The Wave Function and its Properties

We now move from the conceptual framework outlined above to examine how these features are formalized within the mathematics of quantum theory. In QM, a particle is described by a wave function. This wave function represents the state of a particle and is usually indicated by a Greek letter, most often,Ψ, Ω, or Φ. These representations are vectors, and so

can be decomposed into component vectors, ψ,ω, or ϕ.[10] In addition to the state of a particle, we have an operator, which typically corresponds to some observable property, represented as $\hat{A}$ or $\hat{B}$ and their corresponding eigenvalues, *a* or *b*. An Operator can refer to any mathematical operation that changes the quantum system in some way. This includes—but is not limited to—measurements, which as we saw previously must interact with the system in order to measure it. For this reason, operators are sometimes referred to as observables (Bowman 2008, 8). The eigenvalue refers to the numerical quantity of the property being measured. We can relate these values in the following way:

(Eq. 4.1) $$\hat{A}\Psi_j = a_j\Psi_j$$

Equation 4.1 states that for the operator, $\hat{A}$, acting on the state Ψ_j, will produce the eigenvalue a_j (Bowman 2008, 8). In other words, if you measure the wavefunction in state *j*, for the property represented by $\hat{A}$, you will get a single number corresponding to whatever a_j is. Furthermore, because the state represented by Ψ_j when acted on by the operator $\hat{A}$, only will give the value a_j, Ψ_j is said to be an *eigenstate* of $\hat{A}$. To use the language of determinates and determinables, $\hat{A}$ tells you the determinable property you are looking at. Because Ψ_j has a determinate value for that property, it is an eigenstate of $\hat{A}$, and that determinate, a_j is called the eigenvalue. Thus, Eq. 4.1 tells us that the particle in state Ψ_j has that determinate property.

The scenario represented in (Eq. 4.1) is something of a special case. Most often, a quantum state will not be an eigenstate of the operator acting on it. Rather, it will be in a superposition of states. We can represent this as:

(Eq. 4.2) $$\Psi = \sum_{m=1}^{N} c_m\psi_m$$

[10] The general idea is that component vectors are lower case Greek letters, while the single-vector representation is an upper case Greek letter. Though as we will see, which state is a superposition depends on our interests and therefore the distinction is a purely conventional one.

This equation expresses that any state of a quantum system can be represented as the vector sum of a set of *n* component states ((Bowman 2008, 10-11). Importantly, c_m does not represent an eigenvalue here, but rather the expansion coefficient, just as it does in (Figure 2).[11] It tells us how much its corresponding state contributes to the overall magnitude of Ψ. The expansion coefficient tells us an important feature of the wave function: the probability of finding it in the state ψ_m upon measurement. For any particle in state Ψ, the probability of finding that particles in state ψ_m is equal to $|c_m|^2$ ((Bowman 2008, 10-11). Critically, Eq. 4.2 is a statement about the mathematical structure of the wave function, and so holds independently of the observable one is measuring. For this reason, we can always write the wave function as a superposition.

4.2.2 Quantum Superposition

Equation 4.2 might not seem alarming for the dispositionalist. After all, we have encountered superpositions before. We may merely recall that while we may break down vectors into a superposition of its component, each representation is just an alternative way of describing the same, single state. This allows us to create a privileged representation of that state, by which we can identify its dispositional properties. One might hope that the same strategy could be applied in quantum mechanics. Just as in classical mechanics, the superpositions in QM represent a single state of the particle. Why can we not simply again identify a privileged representation, and use that to determine the particle's dispositional properties?

While this seems like a strategy for addressing quantum superposition, it faces a significantly greater challenge than in the classical case. Something interesting happens when we combine equations 4.1 and 4.2. Suppose we want to look at some observable $\hat{B}$, for which Ψ is *not* an eigenstate. When this is the case, measurement will not return a single eigenvalue,

[11] I will use *c* to only refer to the expansion coefficients in order to avoid confusion between the two values.

so Eq. 4.1 does not hold. However, we can always represent Ψ as a superposition of eigenstates by using equation 4.2 to produce the following equation:

(Eq. 4.3) $$\hat{B}\Psi = \hat{B}\sum_{m=1}^{N} c_m \psi_m$$

Because they are eigenstates, equation 4.1 does hold for the states, ψ_m, so they will each have their own eigenvalue, b_m, such that:[12]

(Eq. 4.4) $$\hat{B}\Psi = \sum_{m=1}^{N} b_m c_m \psi_m$$

Equation 4.4 illustrates why the classical strategy for identifying dispositions will not work in the quantum case. In classical mechanics, we made use of the fact that the superposition of component vectors produces a single resultant vector, which we could use to identify an object's dispositional properties. However, because the resultant vector, Ψ, is not an eigenstate of $\hat{B}$, we cannot identify the properties associated with that state on the basis of Ψ. The best we can do is decompose Ψ into its component eigenstates, and identify the determinate properties of those states. Recall that each eigenvalue, b_m, represents a different determinate value of the determinable property represented by $\hat{B}$. Unlike in classical mechanics, where there are numerous representations of a single state with defined properties, Eq. 4.4 shows that the *properties themselves* also exist in a superposition in QM.

The superposition of properties in quantum mechanics makes it unclear how to adapt the quantum formalism to the dispositional schema expressed in Equation 2.5. Let us take stock of some of the challenges. The key issue is that, rather than describing the state of the system in terms of its properties, quantum mechanics identifies a particle's properties in terms of the state of the system. If we want to examine how a property is described by the wave equation, we must read that property into the formalism by selecting an observable. While this is common practice in quantum mechanics—indeed, it is exactly what the Schrödinger equation is meant

[12] This equation is roughly drawn from equation (2.11) in (Bowman 2008, 11). I don't believe this notation is typically used, but I have included it to illustrate the philosophical problem that quantum superposition presents for the dispositionalist, namely, that represents a superposition of determinable properties.

to allow us to do—it illustrates a structural challenge. The dispositionalist strategy to this point has been to identify the aspects of a state that are relevant to a potency by appealing to the nature of the potency itself. However, in quantum mechanics, whether a property even has a definite value now depends on the state. This makes it unclear how we might explain the quantum state fully in terms of dispositional properties.

The most common strategy for addressing this challenge has been to build the indeterminacy of a given property's value into the disposition itself in the form of propensities. Propensities were most prominently developed and championed by Karl Popper and D. H. Mellor in response to quantum mechanics, and some version of the propensity theory is accepted by many prominent dispositionalists(Molnar 2003; Bird 2007; Mumford and Anjum 2010). The idea behind propensities is that if we can treat the superposition of possible properties as itself a dispositional property, then the dispositional reduction of the wave equation can proceed apace. In the following chapter, I will evaluate Popper's and Mellor's respective strategies for characterizing propensities and show that neither allows us to explain the wave function purely in terms of dispositional properties.

CHAPTER 5: PROPENSITIES AND QUANTUM SUPERPOSITION

Because probability is itself a modal concept, it seems natural to synthesize it with dispositions. Probability is generally taken to express some form of quantified modality, though there is debate about what the exact nature of this modality may be, e.g. epistemic, physical, etc. The propensity approach to understanding probability attempts to explain probability in terms of the dispositional properties of objects. Probabilistic dispositions are referred to as propensities, following the terminology popularized by Karl Popper (1959).

All propensity interpretations of probability regard probabilities as objective features of the world, which are reducible to properties of systems or objects. Like all dispositions, propensities are directed towards an outcome. A single instance of the activation of a propensity—flipping a coin, say—is referred to as a trial. However, unlike generic dispositions, the outcome of a trial will always be partial, though exactly in what sense varies between theories. The two most famous propensity theories were proposed by Karl Popper and D. H. Mellor. Both theories illustrate the challenges facing a propensity account of probability and exemplify common strategies for addressing them. In what follows, I will describe each theory, identifying key tensions in their treatment of quantum mechanics.

5.1 Popper's Theory of Propensities

Let us begin with Popper's theory, introduced in *The Logic of Scientific Discovery* (1959). Popper developed the concept of *propensities* to treat probabilities as objective features of the world. His account was partly motivated by the challenges posed by quantum superposition, which led him to imagine propensities as capable of interacting in ways structurally analogous to the behavior of physical forces, such as by interference.

To illustrate this, Popper draws a deliberate analogy between fields of force and what he calls fields of propensities. Just as force vectors have both direction and magnitude,

propensities are characterized by their directedness toward particular outcomes and by a quantifiable weight reflecting their likelihood of manifestation.

This analogy pushes Popper toward a relational view of propensities. As we noted in Chapter 4, the magnitude of a force field at a given point is determined by the combined influence of all relevant components in the system. The field encodes not merely the intrinsic properties of individual objects, but how they are configured and interact. Similarly, Popper holds that propensities are not attributes of isolated objects, but of entire experimental systems. They are relational properties that emerge from the configuration and interplay of the system's components.

For example, the probability of a coin landing heads is not solely a property of the coin—it depends on how the coin is flipped, the surface it lands on, air resistance, and other factors. Each element of the system contributes to the overall set of propensities, and these contributions are aggregated into a single dispositional profile, which determines the probability of each outcome. These weights are then normalized across all possible outcomes.

Critically, Popper insists that propensities manifest in single trials. This means that although the system may have propensities toward multiple outcomes, only one of them will be realized on a given occasion. In this sense, the manifestation of a propensity is always partial: it reveals only one path among many possible tendencies. However, over repeated trials, each propensity will tend to manifest with a frequency that matches its dispositional weight. It is through this cumulative behavior that the probabilistic structure of the system becomes evident.

5.1.2 Popper and Probability

For Popper, probability in quantum mechanics functions just as any other probabilistic system. Just as a fair coin can be part of a biased system to produce a number of heads, the propensities of the wave function are weighted by the whole system. This reinterprets Ψ not as describing the propagation of the particle through space, but as describing the weighted set of

possible paths the particle can take (Popper 1995, 195-196). The wave function, then, predicts the tendency of a system to produce a particle in a given state. From this, the probability upon observation of finding a particle in that state naturally follows.

Popper describes propensities using a function structured analogously to that of probability:[13]

(Eq. 5.1) $Prob(a,b) = r$

This function states that the probability of observing some result, *a*, given the background conditions, *b*, is equal to the value *r,* where $r = 1$ corresponds to certainty in the outcome, *a*. The propensity function:

(Eq. 5.2) $Q(a,b) = r$

describes the strength of the tendency of a system to produce some state, *a,* given *b.* Popper's theory of probability interprets it as describing the propensities of systems, and so the axioms governing it are the same as those probability.[14] This propensity function has a different structure than that describing dispositions in Equation 2.1. This change in structure was necessitated by the indeterminacy of quantum mechanics. Because the same initial conditions can produce a variety of manifestations, it is not possible to model propensities with a function where the manifestations are the outputs. The best viable way to relate propensities to counterfactuals is to treat counterfactuals as holding at the limiting case when $Q(a,b) = 1$. This, coupled with the fact that propensities describe systems on Popper's view, suggests that Popper's theory of propensities will not fit cleanly into the dispositional framework we explored above. Nevertheless, in the next sections, we will examine the prospects for Popper's framework to reduce the wave equation to statements about propensities.

[13] Here, I spell out "Prob" for the probability function to distinguish it from "P" which I have used to designate dispositional properties. I hope this notation helps avoid confusion rather than adding to it.

[14] This position has been criticized by Humphreys, who showed that because Popper's propensity theory was a causal theory, it lacked the symmetry required to validate Bayes' Theorem (Humphreys 1985). However, later philosophers have developed axiomatic systems to describe propensities that they argue are remain strong models of probability in quantum mechanics (Ballentine 2016, 991).

5.1.2 Popper and Quantum Mechanics

We are now able to evaluate Popper's approach to quantum mechanics. Suppose we have a system that has the propensities described by the wave function, Ψ, and measuring the property designated by the observable, $\hat{A}$, we can describe the wave equation as:

(Eq. 5.3) $$\hat{A}\Psi = \sum_{j=1}^{N} a_j c_j \psi_j$$

Each eigenstate ψ_j corresponds to a definite value a_j of the observable $\hat{A}$, and each coefficient cj reflects the contribution of that state to Ψ. Popper's innovation is to interpret this decomposition dispositionally: the squared modulus $|cj|^2$ represents the propensity of the system to yield the outcome aj under measurement.

(Eq. 5.4) $$Q(a_j, \Psi) = |c_j|^2$$

Note, that the operator, $\hat{A}$, does not figure into the formalism. This is because Popper's theory of propensities is not a theory about *measurement*. Rather, propensities describe the probability that a system described by Ψ is in a state which has the property, a_j. $\hat{A}$ is merely a mathematical tool that allows us to alter the representation of the wave function in order to specify the property we are interested in. This means that, in Popper's view, a particle has an entire suite of definite properties at all times (Popper 1995, 141).

Thus, Popper comes up with a rather ingenious way of re-instituting the distinction between waves and particles that is collapsed under quantum mechanics. He treats the wave function as describing the possible states of particles while insisting simultaneously that the properties of the particle itself remain definite. The uncertainty derives from the randomness of interactions between the particle and the rest of the system, and our uncertainty is merely a practical matter, because any attempt to measure a property of the system interferes with the particle, introducing a scattering effect that must be accounted for by altering the propensities of the system. Popper introduced this scheme to avoid the measurement problem and the associated collapse of the wave function. He attributes all the peculiarities of quantum

mechanics to the randomness of interactions between the particle and the rest of the system, and this allows him to maintain a realist interpretation of quantum mechanics without resorting to "quantum jumps" (Popper 1995, 151-156).

5.1.3 Critiques of Popper

At first glance, Popper's theory might appear to be a great fit for the dispositionalist theory we sketched in Chapters Two and Three. Just as we described laws of nature as picking out aspects of a property, Equation 5.4 can be understood as using $\hat{A}$ to identify an aspect of the propensity represented by Ψ. Indeed, this reading has the benefit of making such a decomposition of Ψ explicit.

However, such a move obscures a critical tension within Popper's account: the nature of the properties he is attributing to Ψ. If we take a property, a_j, we can ask whether it itself is a dispositional property. While some properties described by the quantum formalism, such as position, may not be dispositional, others, such as momentum, seem evidently to be dispositional properties themselves. However, if we allow the particle itself to have dispositional properties, this will lead to a contradiction.

Let's take momentum. For a particle, momentum is equal to the change in product of mass times velocity: $p = mv$. This suggests that we can model momentum as the disposition of an object with a certain mass to change positions at a rate given by v. This disposition would have the same structure as our classical dispositions, meaning it would be determinate. Because Popper believes that quantum particles are in fact particles, he would presumably ascribe the particle formula for momentum to the particle. However, if we do this, we get a contradiction. Waves propagate differently than particles, meaning that it is possible to identify a possible state of the particle that has a determinate disposition to be in a state forbidden by the wave function. Thus, we will have ascribed two incompatible dispositions to the system.

One might defend Popper by observing that it is possible for a part of a system to have a disposition that is precluded by the system as a whole. For instance, each force in Figure 1 was disposed to accelerate the barge along a path parallel to that force, but the presence of other forces realized a different disposition in the barge than any one force would have realized by itself. However, this extends Popper's force analogy too far. While he likens propensities to fields of forces, the magnitude of propensities corresponds to a *probability*. Once the system determines which probability is manifested, the disposition has done its work. There are no further dispositions to counteract the disposition we have attributed to the particle, so the contradiction remains.

Can we avoid the tension by refining our understanding of momentum? Perhaps, but doing so seems to leave ambiguous what exactly momentum is. If we try to attribute the wave formulation of momentum of a quantum particle, $p = h/\lambda$, but then we have to apply a wavelength to the quantum particle, undermining the distinction between waves and particles that Popper has curated. We might also adopt the instrumentalist strategy of saying that the particle has the propensity to give a certain momentum reading on a measurement apparatus, but this again undermines both Popper and the dispositionalist realist ambitions. These considerations suggest that we ought to reject Popper's metaphysical picture.

While we have rejected Popper's idiosyncratic interpretation of quantum mechanics, is it possible to disentangle that from his theory of propensities? Unfortunately, the prospects for this are also poor. Popper's theory of propensities is committed to the idea that the wave function describes the propensities of the system rather than the particle. All we can say about the particle is that the system has a propensity equal to the value of $|c_j|^2$ for it to have the property a_j upon measurement, but that is all we can say about it. We still cannot say what it is for the particle to have the property a_j.

One might respond that the quantum formalism tells us that to have the property a_j is to (partly) constitute the corresponding eigenstate ψ_j, but this again will not work. ψ_j is a wave function, and in Popper's view represents the propensities of the system. This creates a dilemma: either ψ_j describes the particle, in which case we have wave functions that describe the system, and a different wave function to describe the particle, which is absurd, or all we can say about a_j is that it is the property of the particle that corresponds with the system having propensity ψ_j, which is unilluminating. Regardless, it is evident that there is no way to use Popper's theory of propensities to reduce the wave equation in terms of dispositional properties.

This brings us back to the problem of privileged representation introduced earlier. Popper's theory attempts to reintroduce a classical-style metaphysics by assigning definite properties to particles and treating the wave function as a probabilistic field over those possibilities. But as we have seen, this leads to contradictions when the properties assigned to the particle are incompatible with the wave function describing it. Moreover, by coopting the wave function to describe the system, Popper's framework leaves only the eigenvalues to characterize the particle itself. He is left, in effect, to construct a determinate state for the particle from what the formalism treats as merely one possible outcome among many. As we showed above, any attempt to construct such a state is doomed to failure. This lack of privileged representation leaves us no way to characterize the properties of a quantum particle itself. This makes the dispositionalist project of grounding laws in dispositional properties unworkable on the Popperian framework.

The above considerations suggest that if Popper's theory fails, it is not because it misrepresents probability, but because it attempts to force an ill-fitting metaphysical structure onto a theory whose formalism resists such representation. In the next section, we will explore whether Mellor's theory fares any better.

5.2 Mellor's Theory of Propensities

Mellor's alternative theory of propensities offers a characterization of their structure of propensities that is very different from Popper's. Mellor regards propensities as analogous to mass; they are "objective, empirical and not relational" (Mellor 1971). Naturally, Mellor insists that propensities are properties of individual objects, not relational properties of experimental set-ups. As we saw above, having a certain mass will produce different outcomes under different conditions, and it is just this feature that Mellor has in mind when he distinguishes between dispositions and probability, or what he calls chances.

5.2.1 Mellor and Probability

For Mellor, chances refer to an experimental set-up, whereas propensities refer to the tendency to manifest an event in some set of counterfactual scenarios. A propensity, properly speaking, cannot be assigned a chance of occurring outside of some situation that could manifest it. For instance, the chance of a coin flip landing heads may be ½, but we cannot ascribe a disposition to land heads of ½ to the coin absent any trial set up where the coin is being flipped. Note, that we can still say that *were the coin to be flipped* (under appropriate conditions) then the chance of its landing heads would be ½, but the disposition to land heads is independent of whether such a flipping occurs, and therefore it makes no sense to ascribe the propensity a value of ½ unqualifiedly.

This allows Mellor to improve on Popper in two respects; first, it situates propensities where they intuitively belong—in the objects themselves. Second, it ascribes probabilities to trials rather than dispositions themselves. This has the interesting implication that the probabilities of an object manifesting its propensity vary based on the type of trial conducted. This allows Mellor to account for the fact that the probabilities associated with an object can vary based on its environment without rendering propensities themselves quite so ephemeral.

Mellor makes a critical distinction here. Whereas propensities refer to properties of an object, probabilities describe events, which are constituted by the instantiation of several properties. This discussion in terms of the outcomes of trials much more closely matches the stimulus-manifestation model we developed in Chapters 2 and 3. Indeed, one of Mellor's criticisms of Popper was that while he used dispositional language, his propensity theory could not be modeled by the counterfactual conditional (Mellor 1971, 69-70; Krips 1989, 315). In contrast, Mellor's theory of propensities explicitly maintains the counterfactual structure. How does he do this while still accounting for probability? He treats probability as the manifestation of the propensity, not as its weight.

5.2.2 The Formal Structure of Mellor's propensities

Mellor's treatment of probability as the manifestation of a propensity allows us to retain the following counterfactual structure:

(Eq. 2.1) $D_{(S,M)}x \leftrightarrow Sx\Box \rightarrow Mx$

Unlike Popper, for whom the counterfactual only applied when a propensity had a weight equal to one, Mellor's propensities are a subset of dispositions: the set whose manifestation is a probability. This means that for propensities:

(Eq. 5.5) $Mx = Prob(Ax,b)$

That is, the manifestation of the propensity of object, x, is the probability that Ax occurs, given *b*, where Ax refers to some event within the scope of the probability manifested by the propensity. For example, the coin's propensity to land heads is manifested in the probability of it landing heads when flipped (Krips 1989, 316). Thus, we can plug the trail in for the stimulus condition, and the probability in for the manifestation, and we have offered a counterfactual description of Mellor's theory of propensities.

We can now apply this dispositional model to the quantum formalism described by Equation 5.3.

(Eq. 5.6) $D_{(aj)}x \leftrightarrow \hat{A}x\Box \rightarrow \text{Prob}(a_j x, \Psi)$

This dispositional statement says that an object has the propensity to yield the eigenvalue a_j iff the measurement of the observable $\hat{A}$, manifests the probability that a_j occurs. We can then generalize across the wave function, Ψ, to describe the dispositional property, P_Ψ so that:

(Eq. 5.7) $\Box(P_\Psi x \rightarrow D_{(aj)}x)$

From this we derive:

(Eq. 5.8) $\forall x((P_\Psi x \ \& \ \hat{A}x) \rightarrow \text{Prob}(a_j x, \Psi))$

Thus, we can state that for all x, if x has the propensity described by the wave function, Ψ, and the particle is measured with respect to the observable, $\hat{A}$, the probability of observing a_j is displayed.

While this formulation looks satisfying, it features a significant flaw. The probability of observing a_j given Ψ is just the square of the projection coefficient, $|c_j|^2$. This allows us to rewrite Equation 5.8 as:

(Eq. 5.8) $\forall x((P_\Psi x \ \& \ \hat{A}x) \rightarrow |c_j|^2 x)$

But now we have lost significant information from the quantum formalism, namely, that a_j is the outcome of the measurement! Furthermore, it remains unclear what it would be to manifest a probability. While Mellor treats probability as the manifestation of a propensity, this move invites a conceptual confusion. A probability is a measure over possible outcomes, not a particular outcome itself. But dispositions, as we've understood them, are directed toward the actual manifestation of a particular state of affairs. In Mellor's framework, at least as we have represented it, there is an explanation of the probability, but no explanation of why a_j occurred on a given trial.

We need some further explanation of the wave equation to successfully reduce it in terms of dispositional properties. Mellor suggests that propensities are grounded in some more fundamental property. He seems skeptical that such properties are dispositional, but if this is

true, then Mellor's propensity theory does not accomplish what the dispositionalist needs it to do—explain the manifestation of an event. If there is some dispositional property for which a_j is the manifestation, then we are again stuck where we were before we began our examination of propensities. Thus, a reduction of the wave function in terms of propensities fails.

CHAPTER 6: CONCLUSION

Our investigation of both Popper and Mellor has shown that a dispositionalist reduction of the wave equation to statements about dispositional properties faces severe challenges that have too often gone under-appreciated within dispositionalist circles. When we attempt to explain quantum mechanics in terms of dispositional properties, we are left unable to explain the nature of the properties of quantum particles, the probabilistic structure of those properties, or both. This suggests that the dispositionalists' goal of explaining the laws of nature purely in terms of dispositional properties may be unattainable. I want to suggest that this is because there is no way to account for what properties a quantum system has due to the lack of privileged representation of the wave function in QM.

However, the dispositionalist should not despair. While the quantum wave function does not include a property that can be characterized dispositionally within the formalism, it may still be possible to offer a dispositional analysis of the *state* itself. Unlike the properties of the wave function, there is a definite state of each quantum system. Framing dispositions in terms of states may help us avoid the superposition problem and clarify the relationship between dispositions and their manifestations.

This suggestion may look like a departure from dispositionalism — and in some sense, it is. But in another sense, it can be understood as a cool for dispositionalism to return to its roots. In *Metaphysics* IX, Aristotle recognizes that speaking about potentiality in terms of properties was insufficient. For him, potentiality was ultimately grounded in the way of being of an object—its state (Beere 2009). A return to this Aristotelian insight may offer the dispositionalist not a retreat, but a path forward: one that grounds modality not in static properties, but in the dynamic actuality of quantum states themselves.

BIBLIOGRAPHY

Ballentine, Leslie E. 2016. "Propensity, Probability, and Quantum Theory." *Foundations of Physics* 46 (8): 973–1005.

Beere, Jonathan. 2009. *Doing and Being: An Interpretation of Aristotle's Metaphysics Theta*. Oxford Aristotle Studies Series. Oxford, New York: Oxford University Press.

Bird, Alexander. 2007. *Nature's Metaphysics: Laws and Properties*. Oxford University Press.

Bowman, Gary. 2008. *Essential Quantum Mechanics*. 1st edition. Oxford: Oxford University Press.

Cartwright, Nancy. 1979. "Causal Laws and Effective Strategies." *Noûs* 13 (4): 419–37.

———. 1983. *How the Laws of Physics Lie*. Oxford University Press.

Ellis, Brian. 2002. *Philosophy of Nature: A Guide to the New Essentialism*. McGill-Queen's University Press.

French, Steven. 2020. "Doing Away with Dispositions: Powers in the Context of Modern Physics." In *Dispositionalism: Perspectives from Metaphysics and the Philosophy of Science*, edited by Anne Sophie Meincke, 189–212. Cham: Springer International Publishing.

Heisenberg, Werner. 2000. *Physics and Philosophy: The Revolution in Modern Science*. London: Penguin Classics.

Humphreys, Paul. 1985. "Why Propensities Cannot Be Probabilities." *The Philosophical Review* 94 (4): 557–70.

Hüttemann, Andreas. 2009. "Dispositions in Physics." In *Debating Dispositions: Issues in Metaphysics, Epistemology and Philosophy of Mind*, edited by Gregor Damschen, Robert Schnepf, and Karsten Stüber, 221–37. de Gruyter.

Krips, H. 1989. "A Propensity Interpretation for Quantum Probabilities." *The Philosophical Quarterly (1950-)* 39 (156): 308–33.

Mellor, D. H. 1971. *The Matter of Chance*. New York: Cambridge at the University Press.

Mill, John Stuart. 1893. *A System of Logic*. London: Longmans: Green & Co.

Molnar, George. 2003. *Powers: A Study in Metaphysics*. Edited by Stephen Mumford. Oxford University Press.

Mumford, Stephen, and Rani Lill Anjum. 2010. "A Powerful Theory of Causation." In *The Metaphysics of Powers*. Routledge.

———. 2011. *Getting Causes from Powers*. Oxford University Press.

Popper, Karl R. 1959. "The Propensity Interpretation of Probability." *The British Journal for the Philosophy of Science* 10 (37): 25–42.

———. 1995. *Quantum Theory and the Schism in Physics*. Edited by W.W. Bartley III. London: Routledge.

Vetter, Barbara. 2012. "Dispositional Essentialism and the Laws of Nature." In *Properties, Powers, and Structures: Issues in the Metaphysics of Realism*, edited by Alexander Bird, Brian Ellis, and Howard Sankey. Routledge.

———. 2015. *Potentiality: From Dispositions to Modality*. Oxford University Press.

Williams, Neil E. 2010. "Puzzling Powers: The Problem of Fit." In *The Metaphysics of Powers*. Routledge.