ABSTRACT

The purpose of this thesis is to explore ontological interpretations of quantum mechanics and present a new ontological structure, which will be called Configuration Space non-Fundamentalism. The structure assumes a 3×10^{80}-dimensional universe, in which reside a non-fundamental, 3×10^{80}-dimensional wave function field and fundamental three-dimensional entities. It will be motivated in the context of other ontological interpretations as one of the most straightforward interpretations of quantum mechanics. I intend for these motivations to show that Configuration Space non-Fundamentalism is worthy of further consideration and specification.

Configuration Space non-Fundamentalism: An Ontological Structure

A Thesis Submitted to the Philosophy Department Faculty of Mount Holyoke College in Partial Fulfillment of the Requirements for the Degree of Bachelors of Arts with Honors.

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CONTENTS

INTRODUCTION

The purpose of this thesis is to introduce a new class of quantum mechanical interpretations and argue that it is worthy of further consideration and specification. I call any interpretation that fits this new model a type of Configuration Space non-Fundamentalism. The theory takes our ordinary three-dimensions to be the fundamental space of the universe, with every fundamental entity existing in three-dimensional space.[1] Grounded in these fundamental entities is a non-fundamental wave function field. The wave function field is an existent, 3×10^{80}-dimensional entity, propagating in a 3×10^{80}-dimensional configuration space. It is represented by a function (the quantum wave function) in the quantum mechanical formalism.

Configuration Space non-Fundamentalism is an ontological structure that exists in logical space. But why should we accept it as worthy of further articulation? I attempt to answer this question by drawing a direct comparison between Configuration Space non-Fundamentalism and two other well-accepted interpretations. By contextualizing Configuration Space non-Fundamentalism within the literature on quantum ontology, we can come to understand its virtues, as well as assess its potential downfalls with a clear and critical eye. As a result, the first part

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[1] We can also think of four-dimensional spacetime as the fundamental space for Configuration Space non-Fundamentalism. I will speak of four-dimensional spacetime as fundamental only when it appears in the relevant literature; otherwise, I assume the fundamental space is three-dimensional. The distinction will not be of consequence in this thesis. When relevant, the reader may consider either three-dimensional space or four-dimensional spacetime as the fundamental space of our universe in accordance with Configuration Space non-Fundamentalism.

of this thesis will be dedicated to introducing the literature I take to be particularly relevant for this contextualization, which will then be followed by a discussion of Configuration Space non-Fundamentalism.[2]

The structure of the thesis is as follows. I use Chapter 1 to give the reader context about the various debates in quantum mechanics, as well as requisite understanding of the formalism and the key concept of grounding.[3] Chapters 2 and 3 will contain detailed descriptions of views that oppose Configuration Space non-Fundamentalism. The focus of Chapter 2 will be Configuration Space Realism, and the focus of Chapter 3 will be Craig Callender's One-State Humeanism. I will draw attention to why we might think each view is favorable, and consider its most pressing objections.

Chapter 4 will be a discussion of Harjit Bhogal and Zee Perry's Two-State Humeanism. This interpretation is unlike the aforementioned ones insofar as it will be presented as a type of Configuration Space non-Fundamentalism. The original motivations for accepting Two-State Humeanism differ substantially from the reasons I give in favor of Configuration Space non-Fundamentalism. I use this chapter to describe the original motivation, along with the view itself.

In Chapter 5, I present and motivate Configuration Space non-Fundamentalism. I draw out why Two-State Humeanism is a type of Configuration Space non-Fundamentalism and how it can be motivated for reasons unlike those given in

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[2] I will not consider every alternate interpretation to Configuration Space non-Fundamentalism. Instead, I have chosen to present views that are most relevant to the main argument of this thesis.

[3] I use the term 'formalism' to refer to the mathematics of quantum mechanics.

the previous chapter. I also discuss ways in which the structure is flexible enough to allow for versions of Configuration Space non-Fundamentalism to be developed in greater detail, consider potential objections to the ontology, and offer replies. I end the thesis with some concluding remarks that will bring together all of these considerations.

CHAPTER 1: SOME BACKGROUND

There are a few concepts underlying the arguments in this thesis that will be important to understand. I use this chapter to provide the necessary background on these concepts. In Section 1.1, I explain parts of the formalism for quantum mechanics that are particularly relevant to later arguments. In Section 1.2, I distinguish between two separate debates in the philosophy of quantum mechanics: how to understand the dynamics of a quantum system and how to best provide an ontological interpretation of the theory.[4] The latter will be the focus of this thesis. Section 1.3 is a discussion of the philosophical concept of grounding, which will later be incorporated into the structure of Configuration Space non-Fundamentalism.

1.1. The Formalism.

I begin with a clarification. I will exclusively consider interpretations of non-relativistic quantum mechanics; all of the physics described in this section is from the non-relativistic theory. Non-relativistic quantum mechanics is an incomplete physical theory insofar as it does not account for relativity theory. But it is substantive nonetheless: enough so that I consider it a worthwhile pursuit to engage with its various interpretations. But first, I must discuss the relevant physics.

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[4] I use the term ‘quantum system’ to refer to any part of the universe in which quantum mechanical phenomena occur and are studied. A ‘closed quantum system’ is one that does not interact with its environment, and an ‘open quantum system’ *does* interact with its environment, including other quantum systems. Notably, we can think of the entire universe as one large system. See Susskind and Hrabovsky (2013) for a more general discussion of physical systems.

The property *spin* refers to the intrinsic angular momentum of a particle. If a particle, p, is spin-up in the z-direction, we write $|z\uparrow\rangle_p$.[5] This means, among other things, that a z-spin measuring device will read 'up' for p. If p can be in the states $|z\uparrow\rangle_p$ and $|z\downarrow\rangle_p$, then it can also be in any state of the form $\alpha\,|x\uparrow\rangle_p + \beta\,|x\downarrow\rangle_p$.[6] Call this a *superposition* of states. Born's Rule tells us that the square of the coefficient of a vector in a superposition gives us the probability of measuring the particle in that state. So the probability of an x-spin device measuring 'up' for p would be α^2. For any superposition $\alpha\,|x\uparrow\rangle_p + \beta\,|x\downarrow\rangle_p$, the particle will certainly be measured x-spin 'up' or x-spin 'down', so $\alpha^2 + \beta^2 = 1$.[7]

We can also represent the spin states of multiple particles. For example, we write $|z\uparrow\rangle_p\,|z\downarrow\rangle_q$ to say particle p is spin up in the z-direction, and q is spin down in the z-direction. Two particles in a superposition of spin states might enter the singlet state, which we can represent as,

$$\frac{1}{\sqrt{2}}\,|x\uparrow\rangle_p\,|x\downarrow\rangle_q + \frac{1}{\sqrt{2}}\,|x\downarrow\rangle_p\,|x\uparrow\rangle_p\,.$$

Born's rule tells us that there is a 50% chance of p being measured spin up in the x-direction and q being measured spin down in the x-direction, and vice

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[5] We can think of the z-direction as corresponding to a z-axis (i.e. the "up" axis) on a graph with three perpendicular axes. Since it is arbitrary which direction of space is considered the z-direction, these specifications are made in advance of an experiment or measurement.

[6] In this case, α and β are complex-valued coefficients. What exactly it means for a system to be in a superposition is not obvious. Giving an account of superposition is part of the challenge of interpreting the dynamics of quantum mechanics. I say a bit more about dynamical interpretations in Section 1.2, though much of that work is tangential to the work in this thesis.

[7] The vectors needn't be in a superposition to abide by Born's Rule. We can equivalently write $|z\uparrow\rangle_p$ as $1(|z\uparrow\rangle_p)$ to see that the square of the coefficient is one; it is certain that the z-spin device will measure 'up'.

versa.[8] But there is a 100% chance that one particle will be measured ‘up’ and the other ‘down’ in the x-direction. Since there is a guaranteed anti-correlation between the spins of p and q, we say the particles are *entangled* with respect to spin; if we measured p to be spin up in the x-direction, we would not have to measure q to know it is spin down in the x-direction.[9]

It is a feature of entangled particles that they appear to depend on each other non-locally.[10] A measurement of p’s spin in one area of space can guarantee the outcome of a measurement of q in another area of space. The correlations occur without any signal traversing the space between the particles, or any other form of local communication between them. This is the phenomenon Einstein famously called *spooky action at a distance*, to express the unintuitive nature of the apparent dependence.

The example with particle spin will become relevant again in Chapter 3, but for our purposes it will also be illuminating to look at entanglement with respect to particle position. To use an example, say p and q can be at coordinates (1,0,0) or (2,0,0), as we would find on a graph with three perpendicular axes.[11] Just like with spin, the particles can enter a superposition in which they are entangled with respect to their position. One such superposition may be represented,

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[8] This is because $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$, for a probability of 50% that the particles be found in either state.

[9] This example comes from Bhogal and Perry (forthcoming).

[10] There are two ways we might understand the word *dependence* here: as causal dependence or as law-like dependence. If I shove a door and it swings shut, we would say my hand *caused* the door to swing shut. This is a case of causal dependence. But let’s say that every time I raise my hand, the door to my room opens. And let’s say the only explanation of the phenomenon is a fundamental, irreducible law, which stipulates that every time I raise my hand, the door will open. Then there is non-local, law-like dependence between my hand and the door.

[11] This example is adapted from Ney (2012).

$$\psi_1 = \frac{1}{\sqrt{2}} \left|(1,0,0)\right\rangle_p \left|(2,0,0)\right\rangle_q + \frac{1}{\sqrt{2}} \left|(1,0,0)\right\rangle_q \left|(2,0,0)\right\rangle_p.$$

Born's rule tells us there is a $\frac{1}{2}$ probability that particle one will be found at location $(1,0,0)$ and particle two will be found at location $(2,0,0)$. Similarly, there is a $\frac{1}{2}$ probability that particle one will be found at location $(2,0,0)$ and particle two will be found at location $(1,0,0)$. And it is certain that one of the particles will be found at $(1,0,0)$ and the other will be found at $(2,0,0)$. Now consider another possible superposition of the same particles:

$$\psi_2 = \frac{1}{\sqrt{2}} \left|(1,0,0)\right\rangle_p \left|(1,0,0)\right\rangle_q + \frac{1}{\sqrt{2}} \left|(2,0,0)\right\rangle_q \left|(2,0,0)\right\rangle_p.$$

Again applying Born's Rule, ψ_2 tells us that there is a $\frac{1}{2}$ probability that particle one will be found at location $(1,0,0)$ and particle two will be found at location $(1,0,0)$. Similarly, there is a $\frac{1}{2}$ probability that particle one will be found at location $(2,0,0)$ and particle two will be found at location $(2,0,0)$. And there is a 100% chance that they will be found in the same location.

Notice the difference between ψ_1 and ψ_2. For the particles described by ψ_1, there is a 100% chance they would be found in different locations upon measurement; for the particles described by ψ_2, there is a 100% chance they would be found in the same location. To represent the particle positions in three dimensions, we would draw a graph with a peak at (1,0,0) and (2,0,0); the amplitudes of the peaks would tell us there is a 50% probability of finding p or q in either location.

However, the graph would fail to distinguish between ψ_1 and ψ_2. It could accurately capture the probability of finding either p or q at a particular location, but it cannot capture the correlations between the particles. In other words, the entanglement phenomena cannot be represented in three dimensions. Instead, we represent ψ_1 and ψ_2 in six dimensions. The graph for ψ_1 would have a peak at at $(1,0,0,2,0,0)$ and another at $(2,0,0,1,0,0)$, whereas the graph of ψ_2 would have a peak at $(1,0,0,1,0,0)$ and another at $(2,0,0,2,0,0)$. The six-dimensional graphs encode information about the particle locations *and* their entanglement.[12]

The quantum wave function is the state of a system of particles over time. It can be represented in much the same way the six-dimensional vectors are represented above. The quantum wave function will be $3N$-dimensional, where N is the number of particles in the universe. So for an estimated 10^{80} particles in the universe, the quantum wave function will be represented on the order of 3×10^{80} dimensions.[13] The evolution, or change of the wave function over time, is given by the Schrödinger equation.[14] Without the wave function, facts about entanglement could not be captured in the formalism.

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[12] We can conceptualize a six-dimensional graph as one with six perpendicular axes; i.e. six axes at a 90% angle to each of the others. Unfortunately, it is beyond our capacities to picture (or depict) a genuinely six-dimensional graph.

[13] I write 'on the order' of 3×10^{80} dimensions to account for variability in how many particles we assume there are in the universe. For the remainder of the thesis, if I say an entity is 3×10^{80}-dimensional, I take it to mean the entity is *on the order of* 3×10^{80} dimensions.

[14] The Schrödinger equation is a differential equation written,

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi,$$

where $i = \sqrt{-1}$ is a complex imaginary number, $\hbar = h/2\pi$ is Dirac's constant, ψ is the wave function, and $\hat{H}$ is the Hamiltonian operator corresponding to the total energy of the system.

The wave function is defined on a $3N$-dimensional configuration space, with a single point in the configuration space corresponding to the configuration of all particle locations at a given time. We can draw a path, or trajectory, through a configuration space to represent the change in position of all particles over time. Think of it like a giant game of checkers. Each checker represents a particle, and each square on the board represents a possible checker position. Each point in the "configuration space" of checkers corresponds to one layout. Moving between those points will show how the checkers move across the board, between layouts, over time.

There is one more point worth addressing. I have already explained why the wave function cannot be written mathematically with fewer than 3×10^{80} dimensions. However, it is possible for the wave function to represent a physical, three-dimensional multi-field. Just as entangled particles can appear to depend on each other non-locally, the multi-field would exhibit non-local dependence between spatially separated parts of the field.[15] It requires 3×10^{80} dimensions for the wave function to *describe* the state of the universe, including the relevant facts about entanglement. But that does not preclude it from representing a three-dimensional entity.

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[15] The project of making sense of a quantum multi-field is not trivial. See Hubert and Romano (2018) for more detail on the multi-field approach to quantum mechanics, as well as arguments in its favor.

1.2. Clarifying the Debate.

When it comes to the question of how to interpret quantum mechanics, there are two separate debates: the ontological and the dynamical. We can think of ontological questions as those that ask, “what is there?” The dynamical considerations can be summed up with, “and what’s it doing?” In both cases, what is being interpreted is the formalism for quantum mechanics; though the formalism helps physicists predict quantum events with great accuracy, it does not say anything conclusive about either debate. I use this section to distinguish the debates, focusing on dynamics in Section 1.2.1, and ontology in Section 1.2.2.

Though the debates are largely separate, not every ontological interpretation on offer is compatible with every dynamical interpretation. However, none of the three most popular dynamical interpretations are explicitly incompatible with Configuration Space non-Fundamentalism; in this regard, the dynamical considerations that follow will remain largely separate from the discussions in this thesis.[16] That said, certain details of any ontological interpretation will vary depending on the dynamical interpretation with which it is paired. In describing the three most popular dynamical interpretations of quantum mechanics, I will make sure to note how Configuration Space non-Fundamentalism changes in accordance with each.

1.2.1. Dynamics.

The primary purpose of dynamical interpretations is to explain how a quantum system evolves over time. The reason it is so difficult to offer a dynamical

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[16] I leave it up to the reader to decide whether some versions of Configuration Space non-Fundamentalism are *more* appealing when paired with certain dynamical interpretations.

interpretation of quantum mechanics is best understood in the context of *the two-path experiment*. In the experiment, a source emits particles, called spin-1/2 particles,[17] which pass through a Stern-Gerlach magnet.[18] The particles emerge from the magnet following either the top or bottom path of the experiment. Reflectors, placed at the top and bottom of the experiment, send the particles through a second Stern-Gerlach magnet.[19] The particles again emerge from the magnet in either the up or down direction, where they hit a detection screen. In this case, every particle is measured as hitting the top of the detection screen.[20]

Now change the experiment by putting a device on one of the reflectors to measure whether the particles traverse the top or bottom of the experimental setup. Run the experiment again. After incorporating the measuring device, there is a difference in what is measured at the end of the experiment: 50% of the particles are measured at the top of the detection screen and 50% of the particles are measured at the bottom. It appears that the presence of a measuring device *changed*

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[17] Though it is crucial to the two-path experiment that the particles used are spin-1/2 particles, the reason why will not be relevant to our purposes. It is notable that all protons, neutrons, quarks, and leptons are spin-1/2.

[18] This kind of magnet is named after physicists Otto Stern and Walther Gerlach. Again, it will not be necessary to know why these particular magnets are used in order to understand the example.

[19] These reflectors are designed so that they do not change the properties of the particles in any way. Their sole purpose is to redirect the particles through the second magnet.

[20] When this situation is described mathematically, nothing conclusive is said about whether the particles traverse the top or bottom of the experimental setup. The formalism only tells us the probability of finding the particles in a certain location. As the particles move towards the middle of the experiment they evolve into a superposition of states, in which there is some probability they would be measured at the top of the experiment and some probability they would be measured at the bottom. It is noteworthy that the principle of superposition leads some physicists and philosophers to believe the particle is spread out over many locations in the system, instead of localized to one point. I will discuss this more when I consider the GRW interpretation of the dynamics.

the outcome of the experiment.[21] It is also well-accepted amongst philosophers (and many physicists) that it would be wrong to simply conclude that measuring the system caused it to change.[22]

Put simply, the goal of interpretation is to explain what occurs in an unmeasured system, about which we cannot generate any experimental evidence. It is also to explain what occurs when a measurement is made on the system, without incorporating the concept of *measurement* into the explanation. There are three popular classes of interpretation for the dynamics: GRW interpretations, many worlds interpretations, and Bohmian interpretations. In the following paragraphs, I will provide a brief account of each view.

According to the GRW interpretation, particles are spread out in space as they move through the system.[23] There is an infinitesimal probability that the particle will "collapse" into a definite state of position. The probability is so small that collapses won't be observed for an unmeasured system. But whenever the particles interact with a macroscopic measuring device composed of many particles, the probability of collapse becomes extremely high. When it does occur, collapse into

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[21] It is noteworthy that the same phenomenon occurs no matter what sort of detection device is used. It also occurs irrespective of whether the device goes off (the particles are to be found in the same location as the device), or does not go off (the particles are not to be found in the same location as the device). The formalism accounts for the difference between the two experiments by including a rule that says the particles "collapse" from a superposition state to a definite location whenever a measurement occurs. The location into which they collapse corresponds to where the measurement indicates they would be found in the experiment.

[22] Perhaps the argument is made most succinctly by John Bell: "The concept of measurement becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory at the most fundamental level . . . And does not any analysis of measurement require concepts more fundamental than measurement? And should not the fundamental theory be about these more fundamental concepts?" Bell (1987).

[23] It is called GRW after Giancarlo Ghirardi, Alberto Rimini, and Tullio Weber, who first put forward the interpretation in 1986.

a definite state is nearly instantaneous. This explains how a particle could fail to collapse in an unmeasured system and be measured in a definite state otherwise.

Like GRW, a many-worlds interpretation also assumes the particles are spread out in space. *Unlike* GRW, the particles never collapse into a definite state of position. To explain why particles appear to be found at localized points upon measurement, the many-worlds theorist assumes a measurement of the system causes the world to branch. With branching, each measurement outcome is realized.[24] It appears in one world that the particle is measured at the top of the experiment. In another, quite similar world, it appears as though the particle is measured at the bottom.[25] Measurement does not cause collapse: it changes the state of the universe, in which new worlds are borne out of branching.

Bohmian mechanics is the only interpretation that does not assume the particles are spread out in space. It gives an account of the dynamics whereby the challenge is that we have insufficient information: we know *how* the particles will evolve over time, but not the exact position of each particle in the quantum system. The conclusion is that an additional equation, called the guidance equation, is required to use the particle positions to specify their evolution.[26] In a many particle

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[24] This is true for systems with more than two possible measurement outcomes; the number of outcomes correspond to the number of new branching worlds.

[25] Since the whole world branches, so does the experimenter. The experimenters in different worlds will make different measurements.

[26] More specifically, the wave function represents a physical field. That field pushes around the particles in the quantum system. The way it determines the motion of the particles is described by the guidance equation. When the system appears to evolve differently in the two-path experiment, it is because only part of the wave function field is influencing the particle.

system, what happens to particle positions in one part of the system can affect what the guidance equation says about a spatially distant part of the system.

What I have described are the three most popular ways to interpret quantum dynamics.[27] Variations of each view exist depending on one's ontological commitments, though the dynamical debate is often considered separately from the ontological debate. Still, I believe it is essential to have a cursory understanding of different dynamical interpretations before trying to make sense of the ontological debate.[28] Whether or not the conversations must affect one another, conclusions we draw from each will have a significant effect on the way we understand our universe.

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[27] For Configuration Space non-Fundamentalism to be compatible with each interpretation, the non-fundamental wave function field in configuration space assigns properties to points in that space. The wave function field evolves linearly in accordance to Schrödinger's equation. From here, each dynamical interpretation suggests a different outcome for Configuration Space non-Fundamentalism:

(1) GRW: The field primarily evolves in accordance to an equation, called Schrödinger's equation. There are no collapse dynamics when the field evolves according to this equation. Occasionally, the field stops evolving according to Schrödinger's equation, and collapses.
(2) Many-worlds: The field evolves in accordance with Schrödinger's equation, and there is never a collapse.
(3) Bohmian mechanics: There is a single, non-fundamental "world particle" in configuration space, which moves in accordance to the guidance equation. The particle moves in the field, which always evolves in accordance to Schrödinger's equation.

The ways in which each dynamical interpretation is understood for Configuration Space non-Fundamentalism is quite similar to how they are understood for Configuration Space Realism, which I discuss in Chapter 2. See Chen (2019) for an explanation of how each dynamical interpretation is compatible with Configuration Space Realism.

[28] And vice versa. Given that there are two significant puzzles for interpreting quantum mechanics, it is essential that we are clear about the challenge posed by each one. It is also valuable to know how, if at all, the solutions to one challenge might affect the other.

1.2.2. Ontology.

In this thesis, I will be concerned with the question of what the wave function represents. Since the wave function is a mathematical representation of the quantum state, we can equally understand the question of quantum ontology to be that of what the quantum state represents.[29] These questions are motivated by a desire to understand how our conception of the universe may be modified to accommodate perplexing quantum phenomena.[30] For although the formalism is greatly successful in the strength of its predictive power, it is also revolutionary.

I proceed with the assumption that the correct ontological interpretation of quantum mechanics will be realist.[31] A realist interpretation of the wave function says it represents an objectively existent entity, and one that is mind-independent.[32] Though I do not defend realism in this thesis, I believe we have good reason to be realists about the wave function. To quote Peter Lewis,

> Why not rest content with quantum mechanics as a good instrument for predicting measurement outcomes and give up on the project of describing the microphysical world? Put in such stark terms, the answer is obvious: it is the business of science to describe the world (2016, p. 43).

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[29] It is important not to allow this terminology to confuse the discussions in this thesis. At various points, I will discuss interpretations of the singlet state and of the wave function. These questions are of a kind; the singlet state is just one way of writing down the wave function for a system.

[30] As Peter Lewis clearly summarizes, this is the project of “describing the world behind the [quantum] phenomena” (2016, p. xvii).

[31] For defenses of realism about quantum mechanics, see Wallace (2012) and Lewis (2016). See Chen (2019) for a survey of realist interpretations of quantum mechanics.

[32] Chen (2019). We can contrast realism with two other common ways to interpret the wave function: instrumentalism and epistemicism. Instrumentalism is the view that the wave function is a successful predictive tool, and nothing more. Epistemicism is the view that the predictions given by the wave function tell us the observer’s uncertainty about the physical situation.

And it will be our business here to interpret the wave function. Every interpretation I present in this thesis is realist about the wave function; this includes Configuration Space non-Fundamentalism, with its physical, non-fundamental wave function field propagating in a higher-dimensional configuration space.

1.3. On the Grounding Relation.

Many ontological interpretations of quantum mechanics assume a grounding relation as part of the view.[33] I use this section to explain what is meant by some entity being grounded in another. There is substantive debate about the nature of the grounding relation, and I do not intend to offer a comprehensive survey of the grounding literature in this thesis. My goal is to give an uncontroversial and concise overview of some important points in the literature. The acceptability of Configuration Space non-Fundamentalism should not fall on whether or not the reader agrees with how I present the grounding relation.[34]

We can think of grounding as a dependence relation that is different in kind from causation; the grounding relation describes dependence relations that cannot be characterized as causal. For example, consider Socrates, the man, and {Socrates}, the singleton set of Socrates. What is the relationship between these two entities? Socrates, the man, does not *cause* {Socrates} to exist. But the two are

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[33] One such interpretation is Configuration Space Realism (see Chapter 2). As mentioned, Configuration Space non-Fundamentalism also incorporates a grounding relation into the structure of the view.

[34] There are certain philosophers who do not believe we should posit any sort of grounding relation. I suggest that those philosophers reformulate Configuration Space non-Fundamentalism however they see fit (namely, without explicit mention of the grounding relation).

not unrelated, because the singleton set of Socrates could not exist if the man had not existed. We call the non-causal relation between the two a *grounding* relation.[35]

If the Socrates example is not illuminating, instead consider the disciplines biology, chemistry, and physics. Biology could not be done without chemistry, nor chemistry without physics. But it would be incorrect to say that the disciplines are causally related; a chemical reaction might contribute to a biological process, but chemistry does not *cause* biology. Here is another case in which it is most natural to posit a non-causal dependence; i.e. physics grounds chemistry, which in turn grounds biology.

In this thesis, I will often say some entity is grounded in another. For Configuration Space non-Fundamentalism, the wave function field is grounded in fundamental three-dimensional entities. By this I mean the wave function field exists *in virtue of* the fundamental entities, or the fundamental entities *give rise to* the wave function field. The type of grounding I describe is metaphysical grounding, which is sometimes said to differ from other types of grounding, including normative grounding in ethics and natural grounding in the sciences.[36] Moreover, though some philosophers offer an analysis of the grounding relation, I will take it to be primitive.[37]

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[35] This example was first presented in Fine (1994).

[36] It is considered controversial whether the grounding relation is unitary, or should be separated into these distinct types of dependence relations. See Schaffer (2009) and Fine (2012) for opposing views on the matter. Schaffer accepts that the grounding relation is unitary, while Fine argues that metaphysical grounding is only one distinct kind. It will be irrelevant to this thesis whether or not such distinctions should be made, so long as it is clear that the type of grounding with which we are concerned is metaphysical.

[37] See Bricker (2006) and Correia (2013) for two analyses of the grounding relation. Bricker argues that the grounding relation exists between a fundamental proposition and a non-fundamental

Further, I must distinguish a full ground from a partial ground. We can understand the former as saying when B is fully grounded by A, B exists *entirely* in virtue of A; i.e. the existence of B does not depend on anything but the existence of A. If B is partially grounded by A, B exists in virtue of A, but not entirely. A classic example uses simple propositions. "P or Q" is true in virtue of P, so P fully grounds "P or Q". Since "P and Q" is in *only* true in virtue of both P and Q, it is partially grounded by P and partially grounded by Q. In the context of this thesis, I take the three-dimensional, fundamental entities of Configuration Space non-Fundamentalism to *fully ground* the wave function field.

What I have offered is a cursory glance at some of the key features of the grounding relation, and how I will understand the relation for Configuration Space non-Fundamentalism. There is much more to be said about grounding, and a robust literature on the the nature of the relation.[38] Though the nuances of the debate may inform the views presented in this thesis, much of it is not immediately relevant. So having provided some background on the grounding relation, I will now set the debate aside as I proceed to the issue at hand: discussing ontological interpretations of quantum mechanics.

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proposition that supervenes on the fundamental proposition. Correia suggests that there are essential truths about what is being grounded and how the grounds connect to the grounded.

[38] For instance, see Schaffer (2009), Rosen (2010), Audi (2012), and the references therein for more discussion of the grounding relation.

CHAPTER 2: CONFIGURATION SPACE REALISM

In this chapter I discuss Configuration Space Realism,[39] which will be the first of two opponent views to Configuration Space non-Fundamentalism considered in this thesis.[40] According to Configuration Space Realism, the wave function represents an existent, physical field. The wave function field is an entity on the order of 3×10^{80} dimensions. The wave function field is a fundamental entity, propagating in a fundamental 10^{80}-dimensional configuration space.[41] Any three-dimensional objects of our everyday experience are either non-fundamental or illusory.

We can think of the wave function field as analogous to an electromagnetic field in classical mechanics. The wave function field propagates through space just like an electromagnetic field. But in this case, the space is on the order of 3×10^{80} dimensions, and the field is 3×10^{80}-dimensional. The wave function field evolves over time, just as an electromagnetic field would, and its evolution is governed by the Schrödinger equation. This is a physical interpretation of the formalism, in

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[39] Configuration Space Realism is one of two names for this view, which is also sometimes called *Wave Function Realism*. Since this is not the only realist interpretation of the wave function, I consider the name Wave Function Realism to be misleading. As such, I choose the terminology *Configuration Space Realism*.

[40] This view was first introduced in Albert (1996) and further developed in Loewer (1996). More defenses of Configuration Space Realism can be found in Albert (2013, 2015), Ney (2012, 2013, 2017, manuscript), and North (2013).

[41] There are two ways for us to understand configuration space. We may take a *substantivalist* conception of space, for which the space itself exists independently of what occupies that space. We may also adopt a *relationalist* conception of space, for which space is defined only by relations between the entities that occupy the space. I do not commit to either interpretation in this thesis.

which the wave function evolves over time in accordance to Schrödinger's equation.[42]

However, we must be careful about how we think of Configuration Space Realism in terms of the quantum formalism. When I described the formalism in Chapter 1, I explained that the number of dimensions in configuration space is determined by the number of particles in the universe: for an estimated 10^{80} particles there is a configuration space on the order of 3×10^{80} dimensions. It is crucial that we do not think of Configuration Space Realism in these terms. The theory assumes configuration space is fundamental, which means the number of *non-fundamental* particles in three-dimensional space cannot determine the number of dimensions in configuration space.

Alyssa Ney suggests that the correct way to think of the number of dimensions in configuration space is to say it corresponds to the number of independent variables necessary for a complete description of the state of the wave function at any time.[43] This only obscures the configuration space realist's problem, because the configuration space realist cannot offer a reason why this number appears to be 3×10^{80}. We know *how* the configuration space realist arrives at their assumption: by observing that there appear to be some 10^{80} particles in our universe. But the configuration space realist cannot appeal to these observations to explain why their fundamental space has 3×10^{80} dimensions. So it remains unexplained.

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[42] For a more thorough discussion of the analogy between a wave function field and electromagnetic fields, see Hubert and Romano (2018).

[43] See Ney (2012).

Until now, the overarching assumption for Configuration Space Realism has been that the fundamental ontology consists of a wave function field propagating in higher-dimensional space. Let's make the story a little more complicated. I have already hinted that there are two ways a configuration space realist can understand our three-dimensional world. They may either say the three-dimensional entities around us are illusory or that they are non-fundamental, physically existent, and derivative of the wave function. Following Emery, I will call the former view *Configuration Space Monism* and the latter *Configuration Space Fundamentalism*.[44]

For configuration space monists, the wave function field propagating in configuration space is all that exists in the physical world. It is not true that there are physical, three-dimensional objects. The wave function field gives rise to three-dimensional appearances, and the experience of three-dimensional phenomena. These are illusions: the appearances of three-dimensional entities exist, but physical objects in three-dimensional space do not.

For the configuration space fundamentalist, it is not the case that the wave function field is all that physically exists. Instead, the higher-dimensional field gives rise to existent, physical, three-dimensional objects. A particularly robust version of Configuration Space Fundamentalism assumes the field gives rise to three-dimensional microscopic particles, which give rise to three-dimensional macroscopic objects, which give rise to our experience of the three-dimensional world.

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[44] See Emery (2017). In her paper, Emery uses the terms *Wave Function Monism* and *Wave Function Fundamentalism*, in reference to the other name for this view: Wave Function Realism. I adapt her terminology to be consistent with my use of Configuration Space Realism.

No matter what, Configuration Space Fundamentalism posits more physical entities than Configuration Space Monism: the wave function field *and* some three-dimensional objects.

In the section that follows, I will detail a prominent argument in favor Configuration Space Realism: that it is the most straightforward reading of quantum mechanics. A similar argument can be made in favor of Configuration Space non-Fundamentalism and I do so in Chapter 5. Then in Section 2.2, I outline three common objections to Configuration Space Realism, each having to do with how the theory accounts for our empirical observations. I conclude the chapter in Section 2.3 with a brief analysis of these objections.

2.1. A Straightforward Reading.

Proponents of Configuration Space Realism are motivated by the belief that it is the most straightforward ontological interpretation of quantum mechanics.[45] To understand what constitutes a *straightforward* reading of the formalism, consider an analogy between quantum mechanics and classical Newtonian mechanics. We understand a straightforward ontological interpretation of classical Newtonian mechanics as one in which laws describe the evolution of physical objects over time. If we are to think of the quantum case analogously, the Schrödinger's equation will govern the evolution of a wave function field over time.[46] More specifically, Peter Lewis argues,

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[45] See Ney (2012) for a clear articulation of this argument.

[46] This argument comes from Ney (2012). In this case, the Schrödinger's equation is our law, and the wave function field is our physical object.

> The wavefunction figures in quantum mechanics in much the same way that particle configuration figure in classical mechanics; its evolution over time successfully explains our observations. So absent some compelling argument to the contrary, the prima facie conclusion is that the wavefunction should be accorded the same status that we used to accord to particle configurations (2004, p. 714).

For Lewis, what the analogy suggests is unmistakable: the straightforward way to understand the wave function is to say it represents an existent, physical object. Implicit in his argument is that we *should* think of classical and quantum mechanics analogously, and it is worth considering why we might want to believe this assertion is true. After all, it is not universally accepted; as Craig Callender writes, "One can reasonably ask why we should take lessons about our ontology from a theory we know is wrong" (2014, p. 3157-3158). It is certainly true that our classical theories are not a complete and accurate description of the world.

One way to dispel the concern that we ought not think of quantum and classical mechanics analogously is to argue that although classical theories are not *strictly* correct, they are also not irrelevant to current theorizing. Concepts from classical mechanics continue to be taught in schools and incorporated into professional research. Perhaps these practices tell us that we can benefit by learning from classical mechanics; the theory needn't be flawless to helpfully inform interpretations of quantum mechanics.[47]

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[47] It also is noteworthy that quantum mechanics is itself an incomplete theory. So although we should be conscious of objections like Callender's, we must be careful about how they're formulated. Let's say we are meant to reject as uninformative any interpretation of a theory that does not provide a complete and accurate description of the world. Then we must reject as uninformative the project in this thesis. We must also reject as uninformative the scholarship of nearly every author cited in this thesis, including Callender. It simply cannot be the case that we should be so strict about what qualifies as an informative analysis of a theory – even a theory that we know is incomplete or not strictly accurate.

There are also ways to circumvent Callender's objection. Configuration space realists have argued that irrespective of analogies to classical mechanics, Configuration Space Realism should be the default view. Their reason is that Configuration Space Realism is the only sufficiently realist interpretation of quantum mechanics. Alyssa Ney calls this the argument from entanglement, and summarizes,

> If one wants to give a realist interpretation of quantum mechanics, then the phenomenon of quantum entanglement forces wave function realism on one. That is, it is not possible to give an objective and complete description of the full range of quantum states, which include entangled states, without recognizing the reality of the wave function (here, the universal wave function) and taking it seriously as a physical field in a high-dimensional space (manuscript, p. 60).

Without reifying the wave function as a fundamental wave function field in configuration space, there is no way to offer a realist account of entangled states. Or so goes the argument from entanglement for Configuration Space Realism.[48]

But the argument from entanglement is insufficient for arriving at the configuration space realist's conclusion. Perhaps to capture the facts of entanglement in a straightforward, realist interpretation of quantum mechanics, the wave function must be reified as a physical field in configuration space.[49] This alone does

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Of course, how accurate a theory must be to consider it informative is another question, and one worth consideration. In the relevant case, the question should inform considerations about whether classical theories have succeeded *enough* to be informative, and whether their failures are relevant to the way they inform Configuration Space Realism. I do not think there are obvious answers to these questions, though further discussion on this point may prove useful for motivating the configuration space realist viewpoint.

[48] See Ney (2012) and North (2013) for versions of the argument from entanglement. See Albert (1996) for an argument that we *must* take the wave function to represent a physical entity.

[49] Even this premise is questionable. It could also be the case that the multi-field interpretation of quantum mechanics satisfies the relevant criteria for being a straightforward, realist interpretation of the wave function. See the end of Chapter 1.1 for a brief discussion of the multi-field interpretation.

not require the wave function field to be a *fundamental* entity, as is suggested by Configuration Space Realism. The implicit assumption in the argument from entanglement is that there should be no non-local dependence between fundamental, spatially separated entities.[50] I will call this the Locality Principle. Only by assuming the Locality Principle can the configuration space realist use the argument from entanglement to conclude that the wave function field must be fundamental.

Perhaps the greatest motivation for the Locality Principle comes from our own experiences and intuitions. If a book falls off of my bookshelf, I will look for a local, causal explanation. Perhaps the wind blew in from my window and pushed the book off the shelf. Perhaps my dog quietly bumped into the bookshelf, causing the book to topple over. No explanation I consider will include some spatially separated entity influencing the book's behavior.[51] And though we are less used to observing law-like dependence, our same intuitions about non-local dependence would most surely remain.

By assuming the Locality Principle along with the argument from entanglement, the configuration space realist ensures that our intuitions about locality are preserved, at least fundamentally. In particular, the configuration space monist ensures that all of the physical entities in their ontology abide by the Locality Principle *and* there is no non-local dependence between physical entities elsewhere in

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[50] Recall from Chapter 1 that there appears to be non-local dependence between spatially separated entities in three-dimensions. But all of the behavior of the wave function field in configuration space is local. By stipulating that the wave function field in configuration space is fundamental, the configuration space realist guarantees fundamental locality.

[51] At least, not without being able to see how the spatially separated entity caused another event that *then* caused the book to fly off the shelf. But this is still ultimately an account of local, causal dependence.

the ontology. Since the configuration space monist explains the three-dimensional world as one that is illusory, they instead accept the appearance of non-local behavior between illusory entities.

However, the configuration space fundamentalist must accept non-local dependence between physical entities into their ontology. The view abides by the Locality Principle, because all of the *fundamental* behavior is local. But the ontology includes a physical, three-dimensional universe that is derivative of the wave function field. As a result, entanglement phenomena will still be observed for these entities, which will manifest as non-local dependence in the three-dimensional space.

The arguments in this section identify the two components of Configuration Space Realism that motivate its proponents. The view reifies the wave function as a physical field. This should satisfy anyone looking for a sufficiently realist interpretation of quantum mechanics, and be a virtue for those who take seriously the analogy to classical physics. And it does so while preserving fundamental locality. Where Configuration Space Realism requires work is in offering an explaining as to why our world appears three-dimensional; I leave objections in this vein for the section that follows.

2.2. On the Appearance of Three Dimensions.

I will use this section to discuss three concerns about Configuration Space Realism. Each involves the difference between our apparent three-dimensional world, and the 3×10^{80} dimensions of the wave function field's configuration space. I will first discuss an objection to Configuration Space Realism called the *Manifest*

Image Problem, which challenges the configuration space realist to explain the appearance of our ordinary three dimensions. I then discuss the objection that Configuration Space Realism is empirically incoherent, because our evidence for the theory is generated by experiments in three dimensions. Finally, I will discuss the incredulous stare objection: that Configuration Space Realism is too absurd to be correct.

2.2.1. The Manifest Image Problem.

To understand the Manifest Image Problem, we must recognize that in the configuration space realist's ontology, no three dimensions of configuration space correspond to our ordinary three dimensions.[52] As a result, the configuration space realist must offer a satisfying story about why we perceive a three-dimensional world. Without such a story, the configuration space realist faces the worry that their view is empirically inadequate insofar as it does not explain why we see what we see. This is the challenge known as the Manifest Image Problem.[53]

Advocates of Configuration Space Realism have offered potential solutions to the Manifest Image Problem. I will present just one of these solutions to give the reader a sense of the kind of work being done to ensure the empirical adequacy

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[52] To clarify, the structure of configuration space is not such that it contains our familiar three dimensions and roughly 3×10^{80} (minus three) *additional* dimensions. Or as Alyssa Ney writes in her unpublished manuscript, "there is no absolute sense in which any single dimension of the $3N$-dimensional configuration space corresponds to the x or the y or the z dimensions any better than any other" (p. 48). We could identify three groups of 10^{80} dimensions and say each corresponds to the x, y, or z dimension. But even this coordinatization would not give the configuration space realist a single dimension of configuration space corresponding to any one of our familiar three dimensions.

[53] The term *manifest image* was first used by Wilfrid Sellars in his article *Philosophy and the Scientific Image of Man*. It has been adopted to refer to our everyday observations of the world, and to describe this particular challenge to Configuration Space Realism. See (Sellars 1962) for the original use.

of Configuration Space Realism.[54] The solution, from David Albert, is to let the wave function field play the functional role of ordinary objects in three-dimensional space. In other words, the wave function field in configuration space plays the role of microscopic three-dimensional particles, or particle-like entities, as it evolves over time. Albert calls this *functional enactment*.[55]

In particular, Albert introduces a function that inputs three-dimensional subspaces of configuration space and outputs the wave function field amplitude at those locations. Albert calls the function for any particular subspace the 'i^{th} shadow of the wave function.[56] The shadows are meant to play the functional role of microscopic objects; we can think of the shadows as matter fields that correspond to particles.[57] The macroscopic, three-dimensional ontology is built from the functionally enacted microscopic particles.[58]

Albert's solution to the Manifest Image Problem is not universally accepted amongst configuration space realists. Alyssa Ney writes in response:

> There just doesn't seem to be anything available in the fundamental ontology of the [configuration space] realist to get something to play the causal-functional role of three-dimensional objects, of things

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[54] The potential solution I present comes from Albert (2013, 2015). See also Ney (2012, 2017, manuscript), Timpson and Wallace (2010), and Wallace (2012) for more potential solutions to the Manifest Image Problem. It is noteworthy that Timpson and Wallace do not endorse Configuration Space Realism, though not because of this issue.

[55] Albert (2013, 2015).

[56] Albert (2015).

[57] Ney (manuscript, 223). For more specifics on how the shadows might play the functional role of microscopic particles, see Albert (2015). An overview of the argument can also be found in Ney (manuscript, p. 222-225).

[58] We must think of the functionally enacted three-dimensional space as a *relational* space; i.e. the space exists only insofar as it is defined in terms of objects standing in relation to one another.

> that move towards and away from one another with various velocities in three-dimensions according to the distance between them (manuscript, p. 228-229).

Put simply, Ney's objection is that Albert's attempt to functionally enact three-dimensional space leaves us with each particle-like microscopic entity in its own three-dimensional subspace of the wavefunction space. As a result, there is no way to define distance between these "particles", because there is nothing that functionally enacts a distance relation between particles.

What the above should demonstrate is that potential solutions to the Manifest Image Problem may be flawed and there is no consensus on the correct way to respond. Work remains to be done to determine whether any of the responses currently on offer is acceptable. It is a pressing challenge for configuration space realists to ensure their view coheres with what we observe in the world. But as of now, it also remains one without an obvious solution.

2.2.2. Empirical Coherence.

A closely related concern is that of the empirical coherence of Configuration Space Realism. The concern is this: the evidence we use to develop quantum mechanics comes from three-dimensional tools and measuring devices. According to Configuration Space Realism, macroscopic measuring devices do not exist. What exists is the wave function field in configuration space. It appears Configuration Space Realism is an interpretation of quantum mechanics that undermines the evidence for quantum mechanics.[59]

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[59] This objection comes from Maudlin (2007).

The issue with the empirical coherence objection is that it assumes Configuration Space Realism denies the existence of macroscopic three-dimensional objects. But consider Configuration Space Fundamentalism, which only denies the existence of *fundamental* macroscopic three-dimensional objects. With a proper solution to the Manifest Image Problem, the configuration space fundamentalist need only make the following two assumptions to also solve the empirical coherence worry.

(1) It is possible that we can gain information about fundamental entities when the tools we use are non-fundamental entities.

(2) It is possible that we can gain information about higher-dimensional entities with the tools of our manifest image.

I will not take on the project of defending these assumptions, though I believe they are plausible.[60] I leave this work to the configuration space fundamentalist.

Still, perhaps the case is not so clear for the configuration space monist. Macroscopic three-dimensional objects do not physically exist for the configuration space monist. It is not enough for the configuration space monist to have an

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[60] I also find it particularly plausible to think physicists experiment and theorize under the assumption that (1) and (2) are true. Consider a Geiger counter, which a physicist may use to gain information about particles. A Geiger counter is a macroscopic object, and not the sort of entity that would typically be considered fundamental. But there is no evidence that physicists infer that if the Geiger counter is non-fundamental, the particles about which it gives us information *cannot* be fundamental. There also seems to be some evidence that physicists accept (2); for example, the tools of our manifest image have been used to conduct experiments that have led to string theory as one model of the universe. Notably, according to string theory, our universe is eleven-dimensional.

All to say, denying (1) and (2) may very well be counter to the assumptions physicists make when theorizing. I do not intend to say that the assumptions made by theoretical physicists should, without consideration or qualification, decide our metaphysics. I do take it as some evidence that to reject (1) or (2) would have broader consequences for the way physicists theorize.

adequate solution to the Manifest Image Problem and agree to (1) and (2), above. They must also accept (3):

(3) It is possible we can gain information about physical entities from illusory tools.

Again, it is not the project of this thesis to defend Configuration Space Realism against the empirical coherence concern. But I do believe it is most difficult to grasp how (3) might be true: how our illusory three-dimensional experiences could give us information about what fundamentally, physically exists.

For both the configuration space fundamentalist and the configuration space monist, a solution to the Manifest Image Problem creates the foundation for a response to the empirical coherence objection. Whether or not a configuration space realist is willing to accept (3) may serve as one deciding factor between an endorsement of Configuration Space Fundamentalism and Configuration Space Monism.[61] Whichever argument the configuration space realist takes, I believe the response is plausible enough for us to say the empirical coherence objection can be subsumed by the more pressing Manifest Image Problem.

2.2.3. An Incredulous Stare.

There is one more objection to Configuration Space Realism that may arise as a result of our manifest image. We experience a three-dimensional world, with three-dimensional buildings, trees, people, and the like. From these experiences

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[61] This assumes the configuration space realist will be most readily willing to accept (1) and (2). Those who are partial to the stated response but regard (3) as implausible may simply find it more desirable to commit to Configuration Space Fundamentalism and deny (3). That said, nothing precludes the configuration space fundamentalist from committing to (3) for other reasons.

alone, it may be natural to conclude that Configuration Space Realism is too unbelievable to accept. It defies intuition that our world could be 3×10^{80}-dimensional. This objection amounts to an incredulous stare: the worry that it simply *must not be the case* that Configuration Space Realism provides a true description of the world.[62]

In response to incredulous stare objections, the configuration space realist can either argue that their view is not so absurd as to be unbelievable, or argue that the objection itself is not worrisome. Alyssa Ney argues the former point in her article *The Status of our Ordinary Three Dimensions in a Quantum Universe*.[63] Ney claims that we have previously found it acceptable to believe views that posit higher-dimensional spaces and should regard Configuration Space Realism no differently. She writes,

> For those of us who take our ontological cues from fundamental physics, the dimensionality of the world we inhabit is something about which we have learned to become quite flexible. The world may appear three-dimensional . . . but if the best physics tell us that the space we inhabit really has four, five, or eleven dimensions, we can, without doing too much damage to our sense of what kind of creatures we are and what kind of world we inhabit, come to understand ourselves as occupying a higher-dimensional space (2012, p. 525-526).

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[62] The first mention of incredulous stare arguments appears in David Lewis's *On the Plurality of Worlds* (1986a), in which he cites such arguments as one of the most persistent objections to modal realism. The name has since been adopted to more generally describe any objection based on the premise that a view is too unbelievable or unintuitive to be correct.

[63] Ney also advocates for the latter point in her manuscript on Configuration Space Realism, in which she concludes, "what is intelligible, even true, may not be easy to believe (p. 263)."

Even if Ney is correct, we may still wonder if Configuration Space Realism is particularly unpalatable. After all, a 3×10^{80}-dimensional space must be radically different from our ordinary three dimensions. In response, I believe the configuration space realist is best suited taking the following position: what is strange about Configuration Space Realism is the *existence* of the 3×10^{80}-dimensional wave function field and not the *number* of dimensions on which it is defined. To use an analogy, string theory is not thought to be more absurd than special relativity, simply because the former posits a universe in eleven dimensions and the latter gives us a picture of the world with four dimensions.[64] It is only relevant that the dimensionality of the wave function is not captured by our manifest image.

If the above is not satisfying, the configuration space realist can still argue that the objection fails to be decisive. This is the position David Lewis takes in *On the Plurality of Worlds*, though his is not a defense of Configuration Space Realism. He says of incredulous stare arguments,

> I once complained that my modal realism met with many incredulous stares . . . We have considered several [argued objections]. I think they have been adequately countered. They lead at worst to standoffs. The incredulous stare remains. They remain unanswerable. But they remain inconclusive (1986a, p. 133).

Our pre-theoretical intuitions about the world may suggest that Configuration Space Realism is unacceptable. But per Lewis' argument, pre-theoretical intuitions cannot

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[64] It might be the case that string theory is thought to be less believable than special relativity for *other* reasons. For example, string theory was developed more recently, and there is not as much empirical evidence in favor of the view. But these factors should be irrelevant to the success of the analogy. What matters is that we do not regard string theory as more absurd by virtue of the number of dimensions it posits for our universe.

alone be leveled as a robust objection.[65] Configuration Space Realism is no worse off because it goes against our gut. Or more simply put, the world may not be as it seems.

2.3. Taking Stock.

To recap, there are two ways to be a configuration space realist: be a configuration space fundamentalist or be a configuration space monist. Subsumed under the same class of interpretation, the views differ substantially with regard to what they say exists. Yet despite their differences, they face the same cluster of objections. Each invites incredulity, as well as concerns about empirical adequacy and incoherence. Similarly, each are motivated as a straightforward reading of quantum mechanics.

As for objections, I consider the Manifest Image Problem to be more worrisome than incredulous stares. My impression is that both Ney and Lewis present successful ways to respond to incredulous stare objections. Even putting these responses aside, I find it absurd to reject an interpretation of quantum mechanics on the basis that it defies intuition, because much of what appears to be true of quantum mechanics defies intuition.[66] In our attempt to better understand what unintuitive

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[65] It is possible to develop versions of the incredulous stare objection that don't simply appeal to intuition. See Emery (2017) for one such objection to Configuration Space Realism.

[66] For example, particles seem to sometimes behave like particles and sometimes behave like waves. It looks as if making a measurement on a quantum system changes what occurs in the system. Entangled particles appear as though they depend on each other non-locally. One reason it is so challenging to interpret quantum mechanical phenomena is that – though successful in its predictions – the theory itself paints a picture of the world unlike any we'd expect.

quantum phenomena suggest about the world, it seems foolish to restrict what is considered possible to interpretations that satisfy our intuitions.

In contrast to incredulous stare objections, I consider the Manifest Image Problem to be a worrisome challenge to Configuration Space Realism. It is essential for any successful theory of quantum ontology to comport with our empirical observations and explain our experiences. However straightforward the interpretation, the configuration space realist must answer to the Manifest Image Problem before assuming it is prima facie correct. And unlike the interpretation itself, those answers do not appear to be so straightforward.

CHAPTER 3: ONE-STATE HUMEANISM

In this chapter, I discuss an interpretation of quantum mechanics presented by Craig Callender in his paper, "One world, one beable."[67] I call the view in question a type of One-State Humeanism; this is in contrast to Two-State Humeanism, which I discuss in Chapter 5. I call it a *one-state* view because it assumes the entire universe exists in a three-dimensional space.[68] And of course, it is a *Humean* view because Callender presupposes Humeanism.

Though not in the name *Two-State Humeanism*, the third defining characteristic of Callender's view is that it assumes a nomological interpretation of the wave function.[69] This interpretation of the wave function is motivated in part by an analogy to the classical Hamiltonian. Like the wave function, the classical Hamiltonian

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[67] Callender (2014).

[68] Two-State Humeanism, which I will argue is a type of Configuration Space non-Fundamentalism, assumes the universe has a three-dimensional state and a 3×10^{80}-dimensional state; thus, it is a *two-state* view.

[69] This is to say, Callender assumes that the wave function represents a law. In particular, he assumes the wave function represents a Humean law. A traditional Humean account of the laws takes them to be axioms that summarize the behavior of entities in a Humean mosaic. The laws supervene on the mosaic, which is described by David Lewis as "a vast mosaic of local matters of particular fact, just one little thing and then another ... We have a geometry: a system of external relations of spatiotemporal distance between points ... And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. For short: we have an arrangement of qualities. And that is all" (1986b). Put simply, we can understand the mosaic as a fundamental four-dimensional manifold of spacetime points, their intrinsic physical properties, and the spatio-temporal relations between them. We define supervenience as follows: if A supervenes on B, then there cannot be a change in the properties of A without a change in the properties of B.

is defined on a high-dimensional space. It describes the motion of physical constituents of reality.[70] Neither the nomological wave function nor the Hamiltonian are regarded as physical entities for the One-State Humean. As a result, Callender assumes there is no obstacle to defining them on a higher-dimensional space.[71]

More must be said to have a complete picture of One-State Humeanism. In quantum theory, the wave function evolves with time. As a result, a meta-law is required to describe the change of the nomological wave function. In quantum theory, the Schrödinger equation describes how the wave function evolves with time; for One-State Humeanism, it represents the relevant meta-law. By accepting a nomological interpretation of the wave function, the one-state Humean also accepts the existence of meta-laws.

Since One-State Humeanism assumes the wave function represents an axiom in a set of laws, there may be question as to whether it can be characterized as a realist interpretation of quantum mechanics. By Callender's lights, the view is realist insofar as the nomological wave function "is part of the representational structure of the laws of physics" (2014, p. 3157). More clearly, the wave function represents an axiom with a privileged status, making it more than a mere predictive

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[70] At the heart of the difference between a Humean and a non-Humean understanding of laws is the question of whether the laws describe entities and their dynamical behavior, or if they govern those entities. Of course, the former is a Humean conception and the latter is non-Humean. See Beebee (2000, p. 578-580) for one account of governing versus descriptive laws. For simplicity, I will speak of the laws as describing the trajectory of particles and the like. I do so without any Humean commitments. If the reader prefers to substitute the word 'determine' for the word 'describe,' it may be done with no change to the content of the arguments in this thesis.

[71] I consider this objection in greater detail in Section 3.2.

tool. It is objective in the sense that it represents more than an observer's uncertainty.[72]

To generate the nomological wave function, Callender adopts a Humean account of laws whereby they are generated from the Humean mosaic using a Best Systems Account.[73] The Best Systems Account generates laws by creating a base language, with a vocabulary that refers only to the intrinsic physical properties of spacetime points. Axioms are created out of the base language, and they summarize facts about the Humean mosaic. Since the Humean assumes the laws are propositions that describe the mosaic (albeit a privileged set of propositions), to find the correct set of axioms is to identify all of the laws of nature.

By the Best Systems Account, the correct set of axioms is the one that is logically consistent, and best balances simplicity and informativeness. Think of simplicity in terms of language: if a single proposition, *P*, were the only law, it would be a simpler account of the laws than if we had a multitude of propositions. To contrast, informativeness is how much the axioms tell us about the Humean mosaic. We can often sacrifice simplicity for informativeness (make every true proposition constitute the laws), and informativeness for simplicity (make "1 + 1 = 2" the only law). Hence it is a requirement for the laws that they best balance the two.

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[72] In other words, Callender's is not an instrumentalist or an epistemicist account of the wave function. A committed realist may still worry that Callender's interpretation does not adequately capture the way in which the wave function should represent an existent entity, though Callender argues that this should not be the case if we take seriously the nomological wave function as privileged.

[73] The Best Systems Account of laws was first introduced in Lewis (1973), and revised in Lewis (1986b, 1994).

For our purposes, we can understand Callender's view as having three key features: all physical entities are three-dimensional, Humeanism is presupposed, and the wave function represents a nomological entity. Insofar as Configuration Space non-Fundamentalism does not share any of these features, it is quite different in kind from One-State Humeanism. As a result, arguments in favor of Two-State Humeanism may serve as objections to Configuration Space non-Fundamentalism.

One such argument is Callender's so-called Lost in Space Problem, which I consider in Section 3.1. Then in Section 3.2, I discuss whether the wave function should be regarded as a law-like entity; this is a concern Configuration Space non-Fundamentalism avoids. I argue in Section 3.3 that Callender's interpretation of the wave function is not compatible with a straightforward Humean understanding of laws. I use Section 3.4 to introduce an objection to Humean interpretations of quantum mechanics, which will be relevant to the considerations in this chapter as well as the chapter to follow.

3.1. The Lost in Space Problem.

The Lost in Space Problem occurs whenever an interpretation of quantum mechanics incorporates two vastly different spaces into its ontology, between which is a mysterious or unspecified relation.[74] The situation invites a number of awkward

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[74] Configuration Space Fundamentalism is a quintessential example of an ontology with two vastly different spaces: one 3×10^{80}-dimensional and the other three-dimensional. The same will be true of Configuration Space non-Fundamentalism.

questions about how entities in one space can be grounded in the other, and how they interact across spaces.[75] Callender says of the challenge,

> These [questions] are not threats to the logical coherence or empirical adequacy of the theory, and some may even be said to be badly motivated; still, if not blemishes on the theory they raise the hope that something better might be possible (2014, p. 3156).

Callender does not consider the awkward two-space questions to be devastating. He does believe they provide sufficient reason to endorse a view that avoids the Lost in Space Problem and endorses One-State Humeanism as one such view.

It will be important not to conflate the Lost in Space Problem with the similar-sounding Manifest Image Problem. The latter is specific to Configuration Space Realism, and calls for an explanation as to why it appears as though our world is three-dimensional. This is unlike the Lost in Space Problem, for which the primary concern is derived from trying to make sense of relations between vastly different spaces.[76] This distinction will be especially important in our discussion of Configuration Space non-Fundamentalism, which avoids the Manifest Image Problem but not the Lost in Space Problem.

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[75] With regard to Configuration Space Realism, Callender writes, “The field in [3×10^{80} dimensions] ‘guides’ an N-particle system in [three-dimensions]. How does this puppet-master operate the puppet without any strings?” (2004, p. 3155).

[76] Here is one way to understand the difference between the two objections. Let’s say we have an ontological interpretation that assumes two physical spaces exist. One of those spaces is ten-dimensional, and the other is eleven-dimensional. The challenge from the Manifest Image Problem would be to explain how we are living in a world with a ten-dimensional space and an eleven-dimensional space, but we experience the world as three-dimensional. Proponents of this ontology owe us an explanation as to how their ontology matches our experiences. However, the Lost in Space concern is that any relations between the ten-dimensional space and the eleven-dimensional space will be obscure, if we can make sense of them at all.

As it stands, the Lost in Space Problem requires greater specification. Callender does not explicitly define a "space," nor justify why the Lost in Space Problem should be taken seriously. I consider the former question question in Section 3.1.1, where I argue that One-State Humeanism only avoids one formulation of the Lost in Space Problem. In Section 3.1.2, I respond briefly to Callender's assumption that only a *Humean* nomological interpretation will avoid the Lost in Space Problem. Section 3.1.3 considers whether the questions raised by having an ontology with two spaces are as problematic as Callender suggests.

3.1.1. The Nature of the Spaces.

One-State Humeanism purportedly avoids the Lost in Space Problem by saying the wave function represents a law. The nomological wave function is still defined on configuration space, but as Callender explains, "There is simply no expectation that laws be functions over three-space, nor that they be decomposable into functions over three-space" (2014, p. 3158). For One-State Humeanism, the nomological wave function exists in the same way a proposition exists. Since the nomological wave function does not represent a *physical* entity, One-State Humeanism avoids the Lost in Space Problem insofar as it is formulated against any view that suggests the existence of physical entities in two different spaces.

This is not the only possible way to formulate the Lost in Space Problem. A stricter version of the Lost in Space Problem might take issue with awkward questions borne out of specifying relations between *any* two spaces. Notably, this stricter formulation will target One-State Humeanism. Though One-State

Humeanism needn't offer an explanation as to how physical entities in different spaces interact, the laws are grounded in the mosaic and *this* relation must still be specified. It is not immediately obvious that the wave function's status as a law will make the grounding relation any less obscure.

One way the one-state Humean can reject the stricter version of the Lost in Space Problem is to say the Humean mosaic exists in a three-dimensional space, but the laws do not exist in *any* space. Though we define the wave function on a configuration space, it does not immediately follow that the law it represents must exist in a space.[77] The apparent conclusion is that the one-state Humean does not have to contend with troublesome consequences of two spaces. However, this response may only obscure the immediate concern: whether awkward questions arise from the grounding relation for One-State Humeanism.

Instead, the one-state Humean can reject the strict version of the Lost in Space Problem by arguing that it targets a number of other plausible grounding relations. In Chapter 1, I used the example of $\{Socrates\}$ being grounded in Socrates. Insofar as they are both abstract entities $\{Socrates\}$ is akin to a Humean law. Similarly, Socrates is akin to the Humean mosaic insofar as both physically exist.[78] So the strict version of the Lost in Space Problem will target both of these relations as mysterious.[79] Perhaps it is preferable to accept the version of the Lost in Space

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[77] Perhaps even if we do say the law exists in an abstract space or a logical space, these might not be spaces in the relevant sense.

[78] Or *existed*, as it were for Socrates.

[79] In other words, if the grounding relation between an abstract entity and a physical entity is mysterious, then it will be mysterious for both of these cases. There are notable differences between Socrates and the Humean mosaic (one being that Socrates was once alive), just as there are notable

Problem that only accounts for interactions between physical entities to prevent it from targeting these other grounding relations.

For the rest of this thesis, I will assume the latter formulation of the Lost in Space Problem is correct.[80] I am not committed to this position, but I do consider the stricter version more controversial for the reasons discussed in the previous paragraph. As a result, I consider both One-State Humeanism and Configuration Space Monism to avoid this objection.[81] I ultimately leave it to the reader to judge which formulation of the Lost in Space Problem should be considered correct.

3.1.2. A non-Humean Defense.

There is another piece of the Lost in Space Problem that requires clarification regarding which views must contend with the objection. Callender suggests that One-State Humeanism only avoids the problem because the wave function represents a *Humean* law. He writes, “Notice that on the governing view, the ‘lost in space’ questions reappear. Where do the laws live? How do they affect the ontology in spacetime?” (2014, p. 3159). Implicit is the assumption that a non-Humean, nomological interpretation of the wave function would render it a higher-dimensional, physical entity governing physical, three-dimensional entities. Only then will the Lost in Space Problem reemerge.

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differences between $\{Socrates\}$ and Humean laws. But these differences should prove irrelevant for the analogy, which only concerns *types* of entities in various spaces, and the relations between them.

[80] Though not explicit in the text, this appears to be how Callender understands the Lost in Space Problem as well. He asserts that One-State Humeanism avoids the Lost in Space Problem, which is only true with this formulation of the objection.

[81] Since Configuration Space Monism assumes three-dimensional entities are illusory, it too needn’t contend with worries about physical entities interacting between spaces.

There are two substantial problems with Callender's claim. The first is that non-Humeans needn't say the laws are physical entities living in a physical space. There is much to be said about the distinction between laws that govern and laws that summarize, largely outside the scope of this thesis. But there is nothing inherent in a governing conception of laws that requires those laws to be concrete. A non-Humean who considers the laws to be abstract entities (and interprets the wave function as nomological) faces no greater challenge from the Lost in Space Problem than does the One-State Humean.

Second, even if the laws are assumed to be concrete entities that govern other entities, it is not required that they inhabit a space other than three-dimensions. The laws can be concrete and exist in three-dimensions. The resulting picture of the world would include concrete laws governing entities in three-dimensions, between which there would be non-local law-like dependence.[82] The non-Humean can give up fundamental locality in favor of a three-dimensional nomological wave function.

The Lost in Space Problem emerges for the governing conception of laws when the view is formulated so the wave function represents a physical entity in 3×10^{80} dimensions. This is not the only possible non-Humean, nomological interpretation of the wave function, nor is there any reason to think it is the default. One-State Humeanism is a convenient solution to the Lost in Space Problem for those already inclined towards Humeanism, but by no means is the non-Humean impeded from offering a nomological solution of their own.

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[82] For an overview of why the dependence would be non-local, see the discussion at the end of Section 1.1.

3.1.3. What Makes the Questions Awkward?

So far, I have operated under the assumption that Callender's "awkward questions" are genuinely problematic. But it behooves us to ask why these questions pose a problem for a view with two spaces; what makes the questions *awkward* or *problematic* instead of *necessary* or *clarifying*? One reason to think the objection has force is because any answer to these "awkward" questions will invite awkward answers – flat out. In other words, answers to these questions will not cohere with our intuitions about the universe.

It is not clear why we should think awkward questions invite awkward answers. But even if they do, the issue with this understanding of the objection is that the Lost in Space Problem is reduced to an incredulous stare. All it is to level an incredulous stare objection is to say a view is simply too absurd to believe. To differentiate between objections, the Lost in Space Problem should not concern the nature of the answers to these "awkward" questions. There must be a reason to think the questions themselves are problematic.

Perhaps instead we should understand the questions as being "awkward" insofar as they are difficult or unanswerable. The latter challenge is baseless if we do not have further cause to think the questions are unanswerable, and Callender presents us with no such reason. I contend that to reject a question as unanswerable because it has not yet been answered is foolhardy. Therefore, the Lost in Space Problem is reduced to the following concern: the questions that arise from trying to make sense of a view with two spaces are difficult to answer.

In this sense, it is misleading to call the questions awkward. This presentation of the problem suggests that questions arising from views with physical entities in two separate spaces are *particularly* obscure in some manner. Certainly, only interpretations that face the Lost in Space Problem will need to contend with challenging questions *of this nature*. But every interpretation of quantum mechanics will grapple with challenging questions of some form; if this were not the case, there would be no debate about how to offer an interpretation of quantum mechanics.

Still, perhaps the questions are particularly challenging to answer. We might understand the Lost in Space Problem as saying that we should prefer to endorse theories that do not force us to answer these specific questions, because they pose a greater challenge than others. Why we should be particularly wary of these questions over others remains unclear.[83] If we do accept that the questions are especially difficult, then the Lost in Space Problem has force.[84] But I contend that the challenge is weak, and will remain so without further explication.

3.2. Is it Actually Law-Like?

As discussed earlier, an analogy between the classical Hamiltonian and the wave function may be used to motivate nomological interpretations. But it would be a mistake to think the two are perfectly analogous. One relevant difference

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[83] At the very least, to believe that these particular problems are greater than those facing other views requires a successful argument to that effect.

[84] The Lost in Space Problem also has some force if it is one's individual preference to avoid accepting an interpretation that contends with these particular issues. Although that said, it seems to me as though one's preferred interpretation tends to drive which questions they are willing to grapple with, and not vice versa.

is that the wave function evolves over time, and the change is described by the Schrödinger equation. There is no analogous time-dependence for the Hamiltonian. As Callender writes,

> The biggest intuitive obstacle to the nomological perspective is that the quantum state doesn't *seem* like the Hamiltonian in certain crucial respects. Indeed, the analogy is hardly perfect . . . The most important [problem] is probably the fact that the wave function seems contingent (and hence non-lawlike) because it is variable. It varies by system and with time (2014, p. 3157).

Callender considers this disanalogy to be the greatest challenge to nomological interpretations of the wave function; perhaps the laws are not meant to evolve with time.[85] No matter the virtues of One-State Humeanism, it will not succeed under the assumption that the wave function is not the right kind of entity to represent a law.

Callender offers two defenses of One-State Humeanism against the charge that the wave function should not represent a nomological entity.[86] The first defense concerns the nature of laws and questions whether we should be resistant to positing time-dependent laws. I consider this defense in Section 3.2.1. The second defense concerns whether it is necessary to assume the wave function represents time-dependent law. I address this second defense in 3.2.2 In both cases, I conclude that there is an important sense in which the defense is inadequate.

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[85] It is noteworthy that this is not the *only* worry we might have about time-dependent laws. Since time-dependent laws require the existence of additional time-independent meta-laws, we might think One-State Humeanism posits too much fundamental structure. Another worry is that positing both laws and meta-laws render some laws more necessary than others. See Belot (2012) for further articulation of the latter concern.

[86] Callender is specifically not arguing that we *should* consider laws to be the sorts of things that can evolve over time. Instead, he argues that the disanalogy between the wave function and the Hamiltonian is not decisive against a nomological interpretation of the wave function.

3.2.1. Evolving Laws.

As a first defense, Callender dismisses the notion that the time-dependence of the wave function precludes us from considering it a law. Just because we have not yet identified an evolving law does not ensure that such laws do not exist. It should be countenanced as a genuine possibility that time-dependent laws exist. Since One-State Humeanism assumes an evolving law, this is all but a restatement of one of Callender's original assumptions. It should offer little comfort to anyone who is genuinely concerned with this feature of the wave function.

To strengthen the defense, Callender argues that concerns about time-dependent laws originate from classical intuitions. He then argues that these intuitions may be faulty when it comes to interpreting quantum theory; as he writes, "perhaps quantum theory is *telling* us something about the nature of the nomological" (2014, p. 3158). What he insinuates is that we should understand the laws in terms of quantum theory, and not vice versa. But he leaves the claim entirely undefended.

So we should be particularly wary of the word *perhaps* here. It is quite easy to say that quantum theory might be telling us about the nature of the nomological. It is just as easy to say our assumptions about what should be considered nomological can inform quantum theory. Without further argument, there seems little reason to accept one claim over the other. It is an interesting possibility that we might revise our understanding of the laws to account for quantum theory. But without good reason to think we should, it is a weak defense of One-State Humeanism.

There is a second issue with Callender's defense, aside from whether quantum theory can tell us about the nature of the nomological. The argument is premised on the assumption that our classical intuitions may be faulty, yet Callender motivates the nomological interpretation by drawing an analogy with a *classical* law. If we are meant to suspend our classical intuitions about laws, then we should wonder why the law-like nature of the Hamiltonian should suggest a law-like nature for the wave function. Callender asks us to suspend our classical intuitions when disanalogy arises, but lean into them where the analogy agrees. Without further explanation as to why we might want to suspend certain classical intuitions and not others, the assumptions are ad hoc.

3.2.2. A Universal Wave Function?

Callender's second defense assumes that the correct interpretation of quantum mechanics will be a beable theory; i.e. a view that assumes that the fundamental constituents of reality are physical and localized. For these theories, he argues that prior to any judgements about time-dependent laws, a distinction must be made between universal and effective wave functions. A universal wave function is one that describes the state of the entire universe, whereas an effective wave function describes a particular sub-system of the universe.[87]

We know that effective wave functions vary by state and time. But Callender argues that we have no principled reason to think *universal* wave functions also vary by state and time. Since beable theories are ultimately concerned with

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[87] In this case, we can think of the universe as one large system.

the nature of the universal wave function, it is possible that One-State Humeanism needn't countenance time-dependent laws. He writes, "the true form of the universal wavefunction is simply a matter of speculation, and therefore, so are the claimed analogies and disanalogies [with the Hamiltonian]" (2014, p. 3158). So the argument goes, if the universal wave function is actually time-independent, then any concern about positing time-dependent laws falls away.

Callender's second defense should not entirely ease concerns about the potentially time-dependent nature of the wave function. As he explicitly says, the nature of the universal wavefunction *is* a matter of speculation. If the nature of the universal wavefunction is simply a matter of speculation, then so is the possibility that the universal wave function is time-independent. For those who do not think the laws should evolve with time, Callender's defense might increase their confidence that an acceptable nomological interpretation is possible. But it is not reasonable to think their worry should be eradicated by the possibility of a solution.

After all, the argument is that we should not be too worried about time-dependent effective wave functions because *we do not know* the nature of the universal wave function. It is difficult to tell *exactly* how worried we should be given these considerations.[88] Given that the nature of universal wave functions is currently a matter of speculation, it is implausible that Callender's response should entirely assuage the relevant concern.[89] When it comes to providing an analysis of

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[88] This is exactly because we don't know the nature of the universal wave function, nor how likely it is to be time-independent.

[89] What Callender offers is not an answer to the challenge; it is hope for an answer to the challenge.

One-State Humeanism, I will continue to consider the view in the context of what we know about effective wave functions, instead of relying on mere speculations about the nature of universal wave functions.[90]

3.3. Not-so-straightforward Humeanism.

One-State Humeanism might have initial appeal for realists who are partial to Humeanism. It retains the fundamental structure of a three-dimensional Humean mosaic, thus preserving any intuition one might have that the world is three-dimensional. It also avoids what I have called the less controversial formulation of the Lost in Space Problem, for those who remain worried about this challenge. But it would be a mistake to let the virtues of One-State Humeanism obscure the crucial fact that it is *by no means* a straightforward Humean interpretation of quantum mechanics; the structure of the Humean view is complicated by the existence of meta-laws.[91]

One appeal of Humeanism is that it tells a straightforward story about what exists. There are fundamental properties at points in a three-dimensional mosaic. One correct set of axioms describes the behavior of everything in the mosaic. And that is all. For One-State Humeanism, the story is not so simple. There remains

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[90] I do this for three reasons. First, I believe it is valuable to offer an analysis of One-State Humeanism as we currently understand the view; should the nature of universal wave functions become clear, the analysis can be revised accordingly. Second, I believe it is sensible to rely on the knowledge we do have of effective wave functions to provide an analysis of One-State Humeanism, rather than relying on speculations about universal wave functions. Third, it is beyond the scope of this thesis to consider every way in which One-State Humeanism may ultimately be spelled out as an interpretation.

[91] This does not mean One-State Humeanism is a more complicated Humean view because it admits time-dependent laws. There is nothing inherently counter to the Humean intuition in positing a time-dependent law. It is only the additional requirement that Schrödinger's equation govern its evolution which causes complications.

a set of axioms summarizing the behavior of entities in the Humean mosaic, but they alone cannot describe what occurs. A second set of axioms must be introduced solely to describe the first, complicating the traditional Humean conception of laws.

If the Schrödinger equation represents a Humean meta-law, then it summarizes the evolution of the nomological wave function. The meta-law is necessary, but its role is distinct from that of the laws. The meta-laws summarize a privileged set of axioms, while the laws summarize the mosaic. On one reading of One-State Humeanism, the laws and the meta-laws compose two separate sets of axioms, adding additional structure to the traditional Humean worldview. On another reading, the laws and meta-laws comprise a single set of axioms, which too adds additional complexity: a subset of these axioms only describe other axioms and the rest describe the mosaic.

In either case, the more complicated structure is subject to further questions. Are the meta-laws also generated by the Best Systems Account? If simplicity in the meta-laws comes at a cost to simplicity in the laws, should one set of axioms be privileged over the other?[92] Can the laws and the meta-laws be considered the same type of entity, when the referent of the former is a physical entity and the referent of the latter is abstract? I will not take on the project of answering these questions. I raise them to demonstrate that One-State Humeanism is revisionary

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[92] For those who prefer the reading of One-State Humeanism on which the laws and meta-laws are one single, complex set of axioms, this question is easily reformulated. Instead, we ask: *If simplicity in the meta-laws comes at a cost to simplicity in the laws, should one type of axiom be privileged over the other?*

and urge any Humean with an initial draw to One-State Humeanism to consider seriously whether it satisfies the Humean intuition.

3.4. A Separability Concern.

Whether or not One-State Humeanism satisfies the Humean intuition, another issue for Humean interpretations of quantum mechanics remains. Not specific to One-State Humeanism, the challenge is broadly that there is tension between Humeanism and the posits of quantum mechanics. I will spell out one particular version of this challenge, due to Tim Maudlin.[93] Maudlin's objection is that the singlet state is an example of a fundamental physical state posited by quantum mechanics, which in tension with the Humean principle of separability:

> Separability: the complete physical state of the world is determined by (supervenes on) the intrinsic physical state of each spacetime point (or each point-like object) and the spatio-temporal relations between those points (2007, p. 51).

Recall from Chapter 1 that the singlet state, written $\frac{1}{\sqrt{2}}\left|x\uparrow\right\rangle_p\left|x\downarrow\right\rangle_q+\frac{1}{\sqrt{2}}\left|x\downarrow\right\rangle_p\left|x\uparrow\right\rangle_q$, is one possible wave function of a system. For particles p and q in the singlet state, a spin measurement of each will either read spin up or spin down. If the spin of one particle is measured, the opposite result will be guaranteed for the other.

It is possible for the intrinsic property of spin in p and q to ensure that each measurement will either read spin up or spin down when measured. However, nothing about the intrinsic properties of p and q will determine the anti-correlation

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[93] Maudlin (2007). Maudlin's is not the only challenge to Humean accounts of quantum mechanics. See Teller (1986) for an interpretation of entanglement phenomena incompatible with separability. See Schaffer (2010) for a more explicit argument that Humeanism "cannot provide an adequate basis for entangled systems" (p. 53).

between measurements of their spin. There is nothing about the intrinsic properties of p and q that can account for the predictions given by the singlet state.[94] If the singlet state is part of the complete physical state of the world and all of its features cannot not be determined by the intrinsic physical properties of p and q (and their spatio-temporal relations), then the complete physical state of the world will not be determined by the intrinsic physical state of each spacetime point. This is in direct tension with the principle of separability.

Given the above considerations, we can understand Maudlin as forcing the Humean to make a choice between the following two positions, for which a denial of both will (at least ostensibly) lead to contradiction:

> (1) Assume the singlet state does not represent part of the complete physical state of the world.
>
> (2) Give up the principle of separability (and thus one of the tenets of Humeanism).

One-State Humeanism avoids the separability objection by accepting (1). Since the one-state Humean assumes the wave function is a Humean law, the singlet state does *not* represent part of the complete physical state of the world. Therefore, it needn't be determined by the intrinsic physical state of each spacetime point, per separability. The tension disappears.[95]

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[94] An objector might wonder why the spatio-temporal relations between p and q cannot determine the entanglement phenomenon of the singlet state. Put simply, we can think of the spatio-temporal relation between p and q as a distance relation. There is nothing in the distance relation which could account for the anti-correlation between p and q's measured spins.

[95] In *Quantum Entanglement, Bohmian Mechanics, and Humean Supervenience*, Elizabeth Miller considers the effectiveness of recovering separability by interpreting the wave function as nomological. See Miller (2014).

However, Callender's response will not satisfy the Humean who agrees with Maudlin that the singlet state should be considered part of the complete physical state of the world. In *What The Humean Should Say About Entanglement*, Harjit Bhogal and Zee Perry develop a version of Humeanism which denies both (1) and (2).[96] Their view is called Two-State Humeanism, and it is the subject of the chapter to follow.

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[96] See Bhogal and Perry (forthcoming).

CHAPTER 4: TWO-STATE HUMEANISM

In the previous two chapters, I described views that are in opposition to any formulation of Configuration Space non-Fundamentalism. The view I describe in this chapter – Harjit Bhogal and Zee Perry's Two-State Humeanism – is one way to spell out Configuration Space non-Fundamentalism. That said, the motivations for Two-State Humeanism and Configuration Space non-Fundamentalism are entirely different in kind. I use this chapter to detail Two-State Humeanism and its original motivations. When I introduce Configuration Space non-Fundamentalism in Chapter 5, I will demonstrate how Two-State Humeanism is a kind of Configuration Space non-Fundamentalism, and motivate it in terms of this alternative perspective.

Two-State Humeanism is motivated as a Humean interpretation of quantum mechanics that preserves separability and allows for entangled states to represent part of the total physical state of the world. It is also formulated to preserve two additional Humean tenets, defined below.

> Physical Statism: all the facts about the world, including the modal and nomological facts, are determined by its total physical state.[97]

> Fundamentality: Facts about the distribution of intrinsic physical states to each spacetime point (or pointlike object) are fundamental.[98]

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[97] Bhogal and Perry (forthcoming, p. 2).

[98] Ibid., p. 3.

For Two-State Humeanism, the Humean mosaic is fundamental.[99] Adopting a Bohmian interpretation of the dynamics, Two-State Humeanism also includes N particles moving in a three-dimensional space, and a single world particle in $3N$ dimensions.

Just like One-State Humeanism, Bhogal and Perry's ontology also includes non-fundamental, physical properties attributed to extended entities or regions of the Humean mosaic. The entities are three-dimensional and satisfy separability. They also satisfy a stronger principle, which Bhogal and Perry deem *strong separability.*

> Strong Separability: The complete physical state of any region R is determined by (supervenes on) the intrinsic physical states (and relations between) R's sub-regions.[100]

Call the Humean mosaic and the non-fundamental physical states that satisfy strong separability the M-state, which does not include any wave functions defined on higher than three-dimensions.[101]

Notice that the M-state just is the entire physical state of the world for the One-State Humean. This is not the case with Two-State Humeanism, for which higher-dimensional wave functions represent part of the total physical state of the world. To account for these additional states, Two-State Humeanism also includes an L-state as part of the total physical state of the world. Whereas the M-state is

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[99] In fact, we can assume it is *all* that is fundamental.

[100] Bhogal and Perry (forthcoming, p. 7).

[101] For example, this does *not* include the singlet state. Bhogal and Perry agree that the singlet state cannot be determined by particles p and q alone.

comprised of states that satisfy strong separability, the L-state includes those that satisfy separability but not strong separability.[102]

The L-state is determined by the totality of intrinsic physical states in the Humean mosaic.[103] It is generated with a variant of the Best Systems Account of laws, first described in Chapter 3. Just as with the laws, a base language refers to the fundamental entities in the mosaic. To generate all of the elements of the L-state, the two-state Humean may introduce new vocabulary, so long as it is introduced without interpretation.[104] Since the new vocabulary is introduced into a system with a base language, and the base language is already interpreted, the uninterpreted vocabulary can come to have an interpretation when linked with the base language. Bhogal and Perry describe the process as follows:

> A system S could introduce a novel, uninterpreted, predicate $M(x)$ and then say that $M(a), M(c)$ and $M(f)$ obtain while $M(b)$ and $M(d)$ fail to obtain (where the lower-case letters are singular terms in the base language). Here we are giving '$M(x)$' content by linking it to already interpreted terms (forthcoming, p. 9).

The modified Best Systems Account generates the laws and the physical elements of the L-state in the same way. But the laws are axioms; they are not physical entities. As a result, a singular process is meant to generate a set of propositions as well as physical states. The two-state Humean must make sense of how

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[102] These states also preserve physical statism and fundamentality in a straightforward manner.

[103] To this point, Bhogal and Perry write, "the elements of the L-state are grounded holistically, that is they are determined by the *entire* mosaic. This is exactly the sort of story the ordinary Humean accepts for the grounding of physical laws – they are determined by the totality of the mosaic. The two-state Humean extends this account to apply to part of the physical state as well, namely the L-state" (forthcoming, p. 8).

[104] Only uninterpreted vocabulary is allowed to be introduced in order to avoid the predicate F problem, which is a common objection to the Best Systems Account of laws. See Bhogal and Perry (forthcoming, p. 17-18) for more on how Two-State Humeanism avoids the predicate F problem.

a systematization procedure for language is sufficient to generate physical states. Bhogal and Perry do not provide a clear explanation here, but I will draw on the text to describe what I believe is the most plausible interpretation of the grounding relation for Two-State Humeanism.

We might understand the elements of the L-state as being grounded in the fundamental Humean mosaic. These states, and not others, exist in virtue of being described by a particular subset of the axioms generated by Bhogal and Perry's modified Best Systems Account; i.e. the axioms that are not considered laws.[105] In other words, the L-state exists in virtue of being part of the best system of the mosaic, and it is grounded in the Humean mosaic.[106] The laws, too, exist in virtue of being part of the best system of the mosaic, and they describe the complete physical state of the world.

Before we consider how Two-State Humeanism is a type of Configuration Space non-Fundamentalism, it will be especially worthwhile to consider objections to the view and some replies. Since Two-State Humeanism is a type of Configuration Space non-Fundamentalism, the objections considered in this section will be ones also faced by Configuration Space non-Fundamentalism. I use Section 4.1 to

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[105] This point is inspired by Ned Hall's unpublished manuscript: "What would make it the case that there are masses and charges is just that there is a candidate system that says so and that, partly by saying so, manages to achieve an optimal combination of simplicity and informativeness" Hall (2010, p. 27).

[106] It is this second point that I take to be the least clear-cut part of the interpretation. Bhogal and Perry write, "In summary, on our view the mosaic is fundamental; the L-state and the laws both depend upon the mosaic and so are non-fundamental, and they depend upon the mosaic in the same way, they are both generated by the best way of systematizing the world" (forthcoming, p. 10). It is not explicitly mentioned that the L-state is grounded in the Humean mosaic. But since the L-state is not a set of propositions, and it is wholly unclear how a set of physical states could be grounded in a set of propositions, I consider this aspect of the interpretation necessary to make sense of the grounding relation for Two-State Humanism.

consider three relevant objections and replies. I offer some additional remarks on Two-State Humeanism in Section 4.2.

4.1. Three Key Objections.

The primary motivation for Two-State Humeanism is that it preserves separability while including the wave function as part of the total physical state of the world; in the clearest terms, it is formulated as a response to Maudlin's separability objection.[107] The resulting picture allows for higher-dimensional entities to be grounded in a three-dimensional mosaic and with that picture comes additional concerns about the consequences of a view with this grounding relation.

I draw out these considerations in the following sections. Section 4.1.1 addresses the concern that higher-dimensional entities cannot be grounded in a three-dimensional mosaic. Section 4.1.2 considers whether Two-State Humeanism captures the correct sort of dependence relation between the wave function and entities in the Humean mosaic. Section 4.1.3 discusses whether Two-State Humeanism can adequately capture the relevant supervenience relation.

4.1.1. Making Sense of the Grounding Relation.

David Albert raises an objection to interpretations of quantum mechanics that do not posit a higher-dimensional space in which the wave function resides.[108] The objection is that wave functions cannot be represented mathematically

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[107] We can think of this wave function as a variant of the wave function field described in Chapter 2. I refrain from using the language of a wave function field in this section to remain consistent with the language used in *What the Humean Should say About Entanglement*. But there is no issue with understanding Bhogal and Perry's reified wave function in these terms.

[108] See Albert (1996).

in fewer than 3×10^{80} dimensions and thus the wave function must be reified in a higher-dimensional space.[109] This objection is of little consequence to Two-State Humeanism, for which the wave function *is* reified in a higher-dimensional space.

However there is a closely related concern: if it is not possible to mathematically represent the wave function in three-dimensions, then perhaps it is not possible to ground a reified wave function in a three-dimensional mosaic. Bhogal and Perry recognize this as a potential worry, but consider it of little consequence. They explain,

> While it's certainly true that the set of all possible quantum mechanical trajectories wouldn't be representable *as trajectories* in a four-dimensional space, there's no such barrier to these possible trajectories being *encoded* in the $3 \times n$ degrees of freedom of n particles moving in 3 dimensions. Indeed, this is the whole point of a *configuration* space – that it reflect the structure inherent in the original space and the degrees of freedom available to its particles. There is nothing "extra" to the $3n$ space than what's already in the mosaic (forthcoming, p. 32).

When Bhogal and Perry write that there is nothing *extra* in the $3N$-dimensional space, the claim should not be taken too literally. Certainly, the wave function is a part of the L-state and not a part of the mosaic. We should instead understand Bhogal and Perry as saying everything in the higher-dimensional space corresponds to entities in the Humean mosaic. Recall from Chapter 1.1 that when particle configurations are represented in configuration space, a single point in that space corresponds to a configuration of particle locations in three-dimensions, and a single

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[109] This line of reasoning may be familiar; it is one of the key motivations for Configuration Space Realism, and I alluded to it in Section 2.1.

trajectory represents the change in these particle positions. It is in this sense that the trajectories are encoded in the Humean mosaic.

While there is no corresponding trajectory as a part of the mosaic, all of the information about entities in the L-state can be found, encoded, in the three-dimensional Humean mosaic. It is this correspondence that makes the grounding relation possible. In fact, the Humean mosaic needn't be fundamental for this to be an effective reply; we can understand the response just by observing the formalism for quantum mechanics. The response should be true for any view that assumes the wave function is grounded in three-dimensional entities.

4.1.2. Incorrect arrow of dependence?

A closely related concern has to do with whether a plausible interpretation of quantum mechanics requires the three-dimensional entities to depend on the wave function. This concern is slightly different to that of the previous section; it may be possible to encode higher-dimensional trajectories in a Humean mosaic without it capturing the correct dependence relation. As Bhogal and Perry write,

> It might also be argued that $3n$ space needs to be taken as fundamental to capture the right dependencies. Specifically, the motion of physical particles, in Bohmian mechanics, is dependent on the state and evolution of the wave function, not on their relative distances in physical spacetime (forthcoming, p. 32).

There are two ways to interpret what is meant by *dependence* in the above passage. One is that the wave function is used to make predictions about entities in the Humean mosaic; it *tells* us how the motion of Bohmian particles will evolve over time. In this sense, the Bohmian particles "depend" on the wave function to "determine" their evolution.[110] The second sense of dependence is literal: entities in the Humean mosaic metaphysically depend on the wave function.

Two-State Humeanism can capture the first sense of dependence. With the Schrödinger equation representing a law that describes the evolution of the wave function, we have all of the requisite information about the evolution of the wave function to tell us how the Bohmian particles move through space.[111] However, it cannot capture the second sense of dependence. Two-State Humeanism is formulated such that the wave function metaphysically depends on the Humean mosaic. This is just the sense in which the Humean mosaic is fundamental and the wave function is not.

We might still wonder what explains the fact that the wave function appears to determine the behavior of more fundamental entities insofar as it provides information about the behavior of those entities.[112] Perhaps if we reversed the direction of grounding, the answer would be clear: the behavior of entities in the mosaic appears to depend on the wave function because they *actually do* metaphysically depend on the wave function. There are two responses to this charge available to the Two-State Humean.

First, the two-state Humean may simply be satisfied without further explanation. There is nothing incoherent about a view that posits as a brute fact that

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[110] This sense of dependence is not literal; the Bohmian particles *only* depend on the wave function insofar as it tells us how their motion evolves.

[111] Bhogal and Perry (forthcoming, p. 32).

[112] Of course, we might turn to our observations of the world to explain *that* the wave function can tell us about the motion of Bohmian particles, but this says nothing about *why* it must be the case.

the wave function provides information about the motion of particles in a three-dimensional space.[113] But perhaps the non-explanation is not satisfying. Alternatively, the two-state Humean can concede that there is more work to be done in order to spell out their view in a way that offers a satisfying explanation as to why the wave function tells us about the Humean mosaic in a way that suggests it dictates the behavior of entities in the mosaic.

4.1.3. Capturing Scientific Possibility.

Here is a third concern we might have about Two-State Humeanism: since the L-state is determined by the mosaic, it should not be possible to have two different configurations of the L-state for any single configuration of the mosaic. In other words, a single configuration of the mosaic should correspond to a unique L-state. But it is commonly assumed in physics that it is possible for there to be a difference in the facts about a higher-dimensional entity with no change in the facts about three-dimensional entities.

It is a version of an old problem for Humeans. The original problem involves making sense of cases in which our best science countenances the possibility of two sets of laws describing the same Humean mosaic; since the Humean laws depend on the mosaic, this leads to the exact objection described above.[114] A number of

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[113] Though not explicit, Bhogal and Perry appear to gesture toward this as their preferred response: "there is a stronger sense of 'dependence' on which particle positions do not, on our account, depend upon the wavefunction. But this is just the sense in which, for the Humean, parts of the mosaic are basic and do not depend on *anything*" (p. 32, footnote 18).

[114] See Maudlin (2007) for a version of this objection. Maudlin writes, "One could, for example, postulate that Special Relativity is the complete and accurate account of space-time structure, and produce another theory of gravitation, which would still have the vacuum Minkowski space-time

solutions to the original problem have been offered by Humeans, any of which the two-state Humean may potentially adapt as a solution to the present concern.[115]

Bhogal and Perry's preferred response involves differentiating between a space of metaphysical possibility and a space of scientific possibility. If something is metaphysically possible, then there is a possible world in which it is the case. If something is scientifically possible, then it corresponds to a model of a possible law. The solution is to say the L-state metaphysically depends on the mosaic, whereas the sense in which the L-state could be different when the mosaic is unchanged is the sense in which it is scientifically possible for such differences to occur. It is not *metaphysically* possible for there to be a difference in the L-state without a difference in the mosaic.

We still might wonder why it is not possible for there to be distinct metaphysically possible L-states for any single configuration of the mosaic. Though not stated by Bhogal and Perry, their assumption appears to be that the modified Best Systems Account uniquely determines the L-state from the mosaic; there is only one way to satisfy separability, and best balance simplicity and informativeness to generate elements of the L-state. The determination relation here is metaphysical, which is why it is not metaphysically possible for there to be a difference in the L-state without a difference in the mosaic. But physicists would still be able to model

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as a model. So under the assumption that no possible world can be governed by the laws of General Relativity and by a rival theory of gravity, the total physical state of the world cannot always determine the laws" (p. 67). See Tooley (1977) for additional exposition of this concern.

[115] For instance, see Loewer (1996), Beebee (2000), and Roberts (2008).

multiple possible configurations of the L-state for any single configuration of the mosaic.

4.2. Not-so-straightforward Humeanism Part 2.

In Chapter 3.3, I argued that One-State Humeanism is not a straightforward Humean view. I intend to use this section to level a similar charge against Two-State Humeanism. To make the case, I need to highlight the role the modified Best Systems Account plays in generating the L-state, and compare that with the way it generates the laws. I hope to show that even beyond the additional structure of new uninterpreted vocabulary, there is a feature of Two-State Humeanism that calls for further adaptation of the Humean view.

I begin with the simple observation that for Two-State Humeanism, the wave function is not a law. For Two-State Humeanism, the laws are summaries of physical states. The L-state is comprised of physical states. The laws and the L-state are generated in the same way, using the modified Best Systems Account. As a result, more work is required to specify how the laws differ from the L-state. We know *that* they differ in kind, but insufficient explanation has been provided as to how the Best Systems Account can generate axioms *and* physical entities.

Here's another way to see the issue. The modified Best Systems Account is meant to generate the Schrödinger equation as a law that describes the evolution of the wave function over time. It is also meant to generate the wave function, which is a physical entity. If they are generated in the same way, there must be some additional feature of the modified Best Systems Account that indicates why the former represents an axiom whereas the latter represents a physical state.

We might think intuition allows us to know which entities belong to the laws and which to the L-state; however, this makes it seem as though we get to decide what is part of the L-state and what is part of the laws. Yet it should be a feature of the Best Systems Account, and not our own intuitions, that makes the distinction. So Bhogal and Perry must answer an additional question: why is it the case that the modified Best Systems Account sometimes generates axioms that we consider laws, and sometimes generates axioms in virtue of which physical states exist?

Without a clear answer, the nature of the laws becomes obscured for the Two-State Humean. Certainly, the laws are axioms that best balance simplicity and informativeness. But there must be more to the story if we are to differentiate between an axiom that is a law and an axiom in virtue of which a physical state exists. We need a straightforward story about how the laws differ from the L-state in order to regard Two-State Humeanism as a straightforward view.[116] One systematization procedure surely cannot generate two different types of entity without some further fact about how they are differentiated.

I contend that these concerns will likely not be enough to shake a committed Humean. The case may not be the same for those who are uncommitted in the debate between Humeanism and non-Humeanism. If Two-State Humeanism is only motivated as a Humean solution to the separability problem, its value as an

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[116] Even then, perhaps the addition of the uninterpreted language is enough to say Two-State Humeanism should never be considered a straightforward Humean view.

interpretation of quantum mechanics will fall squarely within the Humean versus non-Humean debate. And perhaps its obscurities will turn away those who are not so motivated to preserve separability.

In the following chapter, I consider Two-State Humeanism outside the context of the Humean versus non-Humean debate, and demonstrate that it can be motivated irrespective of it being a Humean view. I then argue that these motivations provide reason to further develop interpretations of quantum mechanics with a similar structure to that of Two-State Humeanism. These new interpretations fall under the umbrella of what I call Configuration Space non-Fundamentalism.

CHAPTER 5: CONFIGURATION SPACE NON-FUNDAMENTALISM

I propose that we should accept a new class of interpretations, defined by its particular ontological structure, to be worthy of our consideration and further specification. I call the structure *Configuration Space non-Fundamentalism*, and deem any view that fits the structure to be one type of Configuration Space non-Fundamentalism. Though I will not spell out in detail numerous versions of Configuration Space non-Fundamentalism, I will be careful to indicate where the structure is flexible enough to allow for further specification.

The structure of Configuration Space non-Fundamentalism includes a higher-dimensional space and a three-dimensional space. The higher-dimensional space is on the order of 3×10^{80} dimensions, and in it propagates a 3×10^{80}-dimensional wave function field. All fundamental entities, as well as the everyday objects of our manifest image, exist in the three-dimensional space. The wave function field is grounded in the fundamental three-dimensional entities.[117]

There is much more to be said about why Configuration Space non-Fundamentalism is a valuable structure and how it can be spelled out in greater detail. This will be the project of the sections to follow. In Section 5.1, I motivate Configuration Space non-Fundamentalism as a new class of views, worthy of further

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[117] One way to conceptualize Configuration Space non-Fundamentalism is as an "upside down" Configuration Space Fundamentalism. It is a class of views that take the direction of dependence for Configuration Space Fundamentalism and flip it.

development. In Section 5.2, I indicate areas in which further work may be done to identify various types of Configuration Space non-Fundamentalism. In Section 5.3, I respond to a set of objections that will face any version of Configuration Space non-Fundamentalism. I bring all of these considerations together in Section 5.4.

5.1. Motivations.

It is only sensible to begin our discussion of Configuration Space non-Fundamentalism by considering why this ontological structure has appeal, for there is no reason to further develop an unmotivated class of interpretations. The greatest motivation for accepting Configuration Space non-Fundamentalism is one that is shared with Configuration Space Realism: it allows for a straightforward, realist interpretation of the formalism for quantum mechanics. In Chapter 2.1, I discussed at great length why some authors consider positing a wave function field in configuration space to be the correct way to interpret quantum mechanics. In the words of David Albert,

> [I]t has been essential . . . to the project of quantum-mechanical *realism* . . . to learn to think of wave functions as physical objects *in and of themselves* . . . The sorts of physical objects that wave functions *are*, on this way of thinking, are (plainly) *fields* – which is to say that they are the sorts of objects whose states one specifies by specifying the values of some set of numbers at every point in . . . the universe's so-called *configuration space* (1996, p. 277-278).

The very same reasoning may be used to arrive at the conclusion that Configuration Space non-Fundamentalism is also a straightforward, realist interpretation of quantum mechanics.

It may still be argued that a truly straightforward, realist interpretation of quantum mechanics requires fidelity to the Locality Principle and should posit a *fundamental* wave function field. In Chapter 2.1, I demonstrated that the Locality Principle is an additional assumption made by the configuration space realist, and is not what makes their view straightforward in the relevant sense.[118] I also take it to be the case that fidelity to the Locality Principle is unnecessary for a successful interpretation more generally, and address objections to the contrary in Section 5.3.

Configuration Space non-Fundamentalism differs from Configuration Space Realism in that it provides a straightforward, realist interpretation of quantum mechanics while retaining fidelity to our manifest image. While configuration space realists are readily willing to contend with the Manifest Image Problem to preserve their straightforward interpretation, the configuration space non-fundamentalist needn't make any such trade-offs. There is no corresponding Manifest Image Problem for Configuration Space non-Fundamentalism, because the fundamental entities exist in three-dimensional space; nothing extra must be done to make sense of why the world appears as it does.

There is one more objectionable feature of Configuration Space Realism that is not faced by Configuration Space non-Fundamentalism. Recall from Chapter 2 that the configuration space realist cannot articulate why the wave function field is 3×10^{80}-dimensional. The particular challenge results from the assumption

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[118] By this, I mean that the Locality Principle is irrelevant to whether the view is faithful to the formalism. It is simply a plausible, additional assumption made by the configuration space realist. The sense in which Configuration Space Realism is straightforward and realist is the sense in which Configuration Space non-Fundamentalism is straightforward and realist: it reads the formalism as telling us a wave function field exists in configuration space.

that configuration space is the fundamental space of the universe, when the reason to think configuration space is 3×10^{80}-dimensional comes from the appearance of some 10^{80} particles in three-dimensional space.[119] The configuration space realist must claim that the number of independent variables required for a complete description of the wave function at any time is 3×10^{80}, without any feature of their view providing reason to think the claim is true.

Incorporated into the structure of Configuration Space non-Fundamentalism is the same assumption that the number of dimensions of the wave function field corresponds to the number of independent variables required for a complete description of the wave function at any time. But there is *cause* for this assumption with Configuration Space non-Fundamentalism: the wave function field is grounded in entities in a three-dimensional space. The assumptions we make about the dimensionality of the wave function field can be derived from our assumptions about entities in three-dimensional space.[120] This explanation is simply more robust than the one Configuration Space Realism can provide.

No matter how Configuration Space non-Fundamentalism is further developed, the structure of the view is such that it will always have the advantages

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[119] I articulate this point in depth on page 20.

[120] For example, if we accept a Bohmian interpretation of quantum mechanics, the story is particularly straightforward: there are some 10^{80} particles in three-dimensional space. The number of independent variables required for a complete description of the wave function at any time just is the number of particles in the universe times three degrees of freedom for each particle. Since the wave function field is grounded in these three-dimensional entities, there is a clear explanation as to why it is 3×10^{80} dimensions. With some more nuance, we can arrive at similar conclusions by presupposing GRW or many worlds interpretations of the dynamics.

described in this section. The only ontological interpretations that have this particular set of virtues will be types of Configuration Space non-Fundamentalism. These various types of Configuration Space non-Fundamentalism may also be motivated by additional virtues, irrespective of the considerations in this section. The particular motivations will depend on how versions of Configuration Space non-Fundamentalism are further detailed. As a result, it will be valuable to see exactly where Configuration Space non-Fundamentalism is flexible enough for further interpretation.[121] I address this point the section below.

5.2. Spelling Out the View.

By now, it may be apparent how Two-State Humeanism is one type of Configuration Space non-Fundamentalism. With its reified wave function propagating in a higher-dimensional space and grounded in a fundamental three-dimensional Humean mosaic, Two-State Humeanism has the requisite features to fit the structure of Configuration Space non-Fundamentalism. This means Two-State Humeanism can be motivated for the reasons given in Section 5.1; its appeal extends beyond the Humean motivations presented in Chapter 4.

Two-State Humeanism also has features that are not inherent in the structure of Configuration Space non-Fundamentalism. The most significant of these is that the view presupposes Humeanism and spells out the grounding relation between the M-state and the L-state in terms of a modified Best Systems Account.

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[121] It may be perfectly acceptable to leave undeveloped some of the places in which Configuration Space non-Fundamentalism is flexible enough for further interpretation. Still others might require development to appeal to the preferences of the individual interpreting the view. I leave it to the reader to differentiate between the two given their own predilections.

However, Two-State Humeanism needn't be the only type of Configuration Space non-Fundamentalism compatible with Humeanism. The determination relation for Two-State Humeanism – the modified Best Systems Account – is not inherent to the structure of Configuration Space non-Fundamentalism.[122]

Though compatible with Humean interpretations, Configuration Space non-Fundamentalism assumes no fidelity to Humeanism; it is perfectly permissible to develop versions of Configuration Space non-Fundamentalism without any Humean commitments. In either case, it will be important to provide an account of the grounding relation such that the fundamental entities uniquely determine the higher-dimensional entities.[123] As mentioned in Section 4.1.3, a great deal has been written about how to provide such an account in response to a particular objection to Humeanism.[124] Though Humeanism is often presupposed in this literature, it should be possible to adapt some of the responses so they are rid of all Humean commitments; the non-Humean may do so as they see fit. There is also room for the non-Humean (and the Humean alike) to develop their own set of responses not found in the literature.[125]

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[122] Two-State Humeanism satisfies separability insofar as the higher-dimensional states are determined by the totality of intrinsic physical states of the mosaic. There is nothing inherent in the L-state being generated by the Best Systems Account that satisfies separability. It is perfectly plausible (and may be advantageous) to identify a new determination relation that also satisfies separability and appeals to the Humean intuition.

[123] This needn't be done with an appeal to the modified Best Systems Account. In fact, for those who are dissatisfied with Bhogal and Perry's response to this point, it may be particularly desirable to develop the grounding relation without any mention of the Best Systems Account.

[124] For specific references, see footnote 115.

[125] Here is one potential response that carries no Humean commitments: under the presupposition that Bohmian mechanics is the correct interpretation of the dynamics, the deterministic evolution of the Bohmian particles over all time can uniquely determine the state of the wave function at an instant. I will let the reader decide if this response is plausible and if it is one they might wish to adopt.

Configuration Space non-Fundamentalism also fails to provide an explanation as to why it appears as though the behavior of three-dimensional entities is determined by the wave function. I discussed this point in Section 4.1.2, and concluded that further explanation is not necessary, although it may be desirable. For those who believe further explanation is desirable, there is room to explore whether a specified account of the grounding relation can be formulated to help provide a more robust explanation.[126]

Now to the final point of this section. The nature of fundamental laws is mysterious, and much important work has been done to provide an account of the laws.[127] Configuration Space non-Fundamentalism assumes neither Humean nor non-Humean commitments; it is compatible governing and summarizing accounts of laws. As a result, those with previous commitments to a view about the laws of nature can develop a version Configuration Space non-Fundamentalism which incorporates these commitments. Otherwise, Configuration Space non-Fundamentalism leaves space to decide such commitments without restriction.

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[126] If not, we should recognize that this could be considered a reason for which an objector might take issue with Configuration Space non-Fundamentalism. It would then become one of many trade-offs a proponent of Configuration Space non-Fundamentalism would have to make in order to defend the view.

[127] For instance, see Earman and Roberts (2005a and b) for a particular characterization of Humean laws. See Maudlin (2007, p. 17-18) for an argument that the laws are primitive entities which tell us the space of physical possibility. See Carroll (2008) for an argument that the laws are non-accidental, non-coincidental, and cannot be explained by anything else in nature. The first of these three views is Humean, and the latter two are non-Humean.

5.3. Objections and Replies.

Just as every version of Configuration Space non-Fundamentalism can be motivated by the same set of advantages, there are certain objections that will face every specification of the ontological structure. I use this section to address three such objections, the first two of which should be familiar to the reader. These are incredulous stare objections and the Lost in Space Problem. I will briefly consider them in Sections 5.3.1 and 5.3.2, respectively. I then use Section 5.3.3 to address the objection that Configuration Space non-Fundamentalism violates the Locality Principle, to the detriment of the view.

5.3.1. Incredulous Stares.

Though there is a simple explanation for our manifest image on any version of Configuration Space non-Fundamentalism, the ontological structure may still be met with incredulous stares. Configuration Space non-Fundamentalism assumes a 3×10^{80}-dimensional wave function field exists in a 3×10^{80}-dimensional configuration space. This is not an assumption we would make with an appeal to intuition alone.

I discussed incredulous stare objections at great length in Section 2.2.3 and again in 2.3., in the context of Configuration Space Realism. In keeping with Alyssa Ney, I argued that we can be flexible about how we view our world when it comes to the number of dimensions we inhabit.[128] In keeping with David Lewis, I argued that pre-theoretical intuition cannot provide good reason to reject an interpretation.[129]

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[128] Ney (2012, p. 525-526). The direct quote can also be found on page 32 of this thesis.

[129] Lewis (1986a, p. 133). The direct quote can be found on page 33 of this thesis.

I concluded that incredulous stare objections, without further development, are of little consequence to Configuration Space Realism. I adopt the same response here for Configuration Space non-Fundamentalism.

5.3.2. Lost in Space.

With a space of higher-dimensional entities and a space of three-dimensional entities, Configuration Space non-Fundamentalism will be subject to Craig Callender's Lost in Space Problem.[130] In Section 3.1.3, I considered whether the concern has any force by discussing the many ways we can interpret the worry. I concluded that the challenge is weak, or at the very least, requires further development. As a result, I believe the Lost in Space challenge is of little concern to Configuration Space non-Fundamentalism.

There is still a chance that my defense has not satisfied those who are most taken by the objection. In this case, notice that Configuration Space non-Fundamentalism is no worse off than Configuration Space Fundamentalism with respect to the problem. Perhaps it is simply a consequence of certain straightforward, realist readings of quantum mechanics that awkward two-space questions will arise. It is up to the individual to decide whether this is a trade-off they are willing to make, though I contend that it is not a poor trade-off at all.

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[130] Callender (2014). This should be true no matter how we formulate the concern, as discussed in Section 3.1.1.

5.3.3. Fundamental non-Locality.

Configuration Space non-Fundamentalism is in violation of the Locality Principle. Recall from Chapter 2.1 that the Locality Principle states that there should be no non-local dependence between fundamental, spatially separated entities. Given that all fundamental entities are three-dimensional for Configuration Space non-Fundamentalism, the structure allows for non-local dependence between fundamental, entangled particles. Perhaps it is to the detriment of Configuration Space non-Fundamentalism that it allows for fundamental non-locality.

The most plausible reason to take issue with Configuration Space non-Fundamentalism on this point is to say a violation of the Locality Principle also violates our intuition about the way entities interact. Everything we observe about the macroscopic world suggests that it is impossible for entities to depend on each other non-locally. Since locality is an intuitive posit, it seems especially important to retain it when it comes to fundamental entities.

We can think of this objection as one particularly significant version of an incredulous stare objection.[131] Though the response to incredulous stare objections presented in Section 5.3.1 should be applicable here too, I will offer a second defense against this objection for Configuration Space non-Fundamentalism.

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[131] After all, the objection is founded on the assumption that it is difficult to make sense of fundamental non-locality; it is against all intuition and experience that the world is fundamentally non-local. Notice that this sounds very similar to saying *it is against all intuition and experience that there exists a higher-dimensional configuration space.* That said, fundamental non-locality defines our understanding of the world in a way that positing higher dimensions might not. This is the sense in which the objection is particularly pressing. See Section 2.2.3 and Ney (2012, p. 525-526) for more on how we can be flexible about how we understand the dimensionality of our world.

The defense I offer is similar to that of section 5.3.2: Configuration Space non-Fundamentalism is no more challenged by locality concerns than Configuration Space Fundamentalism.

Notice that the same three-dimensional, entangled particles depend on each other non-locally for both Configuration Space Fundamentalism and Configuration Space non-Fundamentalism. The relevant difference between the two is that only the former assumes these are fundamental entities. In some respects, the difference shouldn't matter. It is no more intuitive to think the behavior of a person in Australia may depend on the behavior of a person in Canada than it is to assume fundamental, entangled particles depend on each other non-locally.[132] There is some degree to which non-locality will always be unintuitive.

The configuration space fundamentalist can argue that they are still in better standing than the configuration space non-fundamentalist, because all non-local behavior between entities in their view can be reduced to fundamental local behavior. Nothing in the view "bottoms out" in non-local behavior. This is a plausible argument for why the Locality Principle should be formulated to account only for fundamental, non-local dependence. But the efficacy of the argument is deceptive in the case of Configuration Space Fundamentalism.

There is nothing in the configuration space fundamentalist's ontology that clearly allows the non-local behavior of non-fundamental entities to be reduced to

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[132] The former is quite obviously an example of spatially separated, non-fundamental entities (i.e. people).

fundamental local behavior. Configuration Space Fundamentalism can try to explain away the non-fundamental non-locality by identifying correlations between the non-local behavior of entangled particles and the local behavior of the wave function. But the configuration space non-fundamentalist can identify the same correlations; they should occur no matter which entities are taken to be fundamental. If this is the only sense in which Configuration Space Fundamentalism can explain away non-locality, it is in no better standing than Configuration Space non-Fundamentalism.

Even more to the point, identifying correlations between the behavior of the wave function and the behavior of entangled particles does not seem to reduce non-fundamental, non-local behavior to fundamental, local behavior in the relevant sense. A more robust explanation is required to meet our intuitions: one that shows how the wave function might "push around" or determine the behavior of non-fundamental entities in a way that explains their non-local behavior in terms of local behavior.

I contend that any such robust explanation will only come *after* the configuration space fundamentalist solves the Manifest Image Problem. If the relevant solution to the Manifest Image Problem includes an explanation of the kind described above, then Configuration Space Fundamentalism may preserve some of our intuitions about locality. But I am skeptical that any such explanation exists.[133]

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[133] I find it implausible to think that any solution to the Manifest Image Problem will be able to capture the relevant relationship between two vastly different spaces: one that is robust enough to offer the kind of explanation required to satisfy our intuitions about locality.

In either case, no such solution is currently on offer; perhaps no such solution will ever be on offer. Which means, at least for the time being, Configuration Space Fundamentalism and Configuration Space non-Fundamentalism are exactly on par when it comes to locality concerns.

5.4. Looking Back.

Choosing which interpretations of quantum mechanics to develop and defend is all about making trade-offs. A nomological interpretation of the wave function is incompatible with the guarantee of time-independent laws. It is impossible to read the wave function as representing a field, abide by the Locality Principle, and retain a fundamental ontology in three-dimensions. In fact, it seems as though we cannot be realists about quantum mechanics without drastically revising how we understand the state of our universe.

The question becomes one of which trade-offs we are willing to make and which motivations are most compelling. I present Configuration Space non-Fundamentalism as a structure that is motivated by a straightforward, realist interpretation of quantum mechanics: one that preserves our manifest image without any challenge and offers a clear explanation as to the dimensionality of configuration space. I believe these motivations make Configuration Space non-Fundamentalism worthy of further development, despite additional challenges accepted as part of the structure.

I will not pretend that Configuration Space non-Fundamentalism is the most intuitive structure of our world. Nor is it the one at which we would arrive by our everyday observations and imaginings alone. But I see the project of interpreting quantum mechanics as one that asks us to set aside our intuitions and look towards the science to help us better understand our world. It is for this reason that I remain partial to arguments for straightforward readings of quantum mechanics. And it is one of many reasons why I believe Configuration Space non-Fundamentalism is worthy of defense.

CONCLUSION

There are many more interpretations of quantum mechanics on offer than what has been described in this thesis. I chose to discuss Configuration Space Realism, One-State Humeanism, and Two-State Humeanism because I believe these three views best contextualize Configuration Space non-Fundamentalism. Each of the three views considered in Chapters 2-4 is is respectable on its own merits, though they are all different in kind.

I began by discussing Configuration Space Realism, which shares many motivations with Configuration Space non-Fundamentalism. I presented it as the heretofore only straightforward, realist interpretation of quantum mechanics of its kind, primarily supported by arguments from Alyssa Ney and David Albert. In doing so, I drew out the Locality Principle as a key assumption made by configuration space realists. I also presented two common objections to Configuration Space Realism: the Manifest Image Problem and incredulous stare objections. I regarded the former as a greater issue for Configuration Space Realism and later noted that Configuration Space non-Fundamentalism only contends with the latter.

I then considered One-State Humeanism and introduced the option of a nomological interpretation of the wave function. I discussed how Craig Callender's analogy between the wave function and the classical Hamiltonian is imperfect because only the former is time-dependent; for those who are not readily willing to accept time-dependent laws into their ontology, One-State Humeanism is not ideal. I then argued that One-State Humeanism could not account for a straightforward Humean intuition. In contrast, Configuration Space non-Fundamentalism is flexible as to what constitutes the laws and can account for such intuitions; it may admit time-dependent laws into the ontological structure, but there is no such requirement.

Afterwards, I pivoted to discussing Two-State Humeanism, which I later presented as a type of Configuration Space non-Fundamentalism. I used the chapter on Two-State Humeanism to discuss its original Humean motivations and present its most pressing objections. Worries about Two-State Humeanism had to do with the nature of the grounding relation: whether it captured the correct dependencies and accounted for how fundamental three-dimensional entities might uniquely determine higher-dimensional states. These considerations came up again in my discussion of Configuration Space non-Fundamentalism.

When presenting Configuration Space non-Fundamentalism, I began with a description of how to understand the ontological structure. In keeping with arguments in favor of Configuration Space Realism, I motivated Configuration Space non-Fundamentalism as a straightforward, realist interpretation of quantum mechanics. I then drew on considerations about Two-State Humeanism to help highlight the ways Configuration Space non-Fundamentalism could be further developed.

I also considered three objections to Configuration Space non-Fundamentalism: incredulous stare objections, the Lost in Space Problem, and worries about its violation of the Locality Principle. I had already presented responses to the first two objections in other areas of the thesis, which I adopted as responses on behalf of Configuration Space non-Fundamentalism. I then argued that Configuration Space Fundamentalism no better captures our intuitions about locality than Configuration Space non-Fundamentalism.

I hope to have shown that the structure of Configuration Space non-Fundamentalism can be motivated by a unique and compelling set of virtues. I further hope to have demonstrated that in contrast to two respectable interpretations (and incorporating a third), the trade-offs made by Configuration Space non-Fundamentalism are not unreasonable. If I have successfully argued for these two points, then I believe it is a structure worthy of further development and consideration. It is no easy task to make sense of quantum mechanics. But then all the more reason for us to consider new ways to interpret the theory, so long as those interpretations are sufficiently motivated.

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