ABSTRACT

Title of Dissertation: A GROUNDWORK FOR PERSPECTIVAL QUANTUM MECHANICS

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There has recently been a renewed focus on 'perspectival' quantum theories. which simultaneously maintain the existence of single measurement outcomes and the universality of unitary evolution. At the same time, these theories have come under attack with results by Frauchiger and Renner, Baumann and Wolf, and others. This dissertation aims to respond to a number of these attacks by providing a groundwork for these types of theories.

To lay this groundwork I focus on *encapsulated* measurements, which involve an isolated observer and a superobserver (who measures the observer). I first distinguish between *invasive* and *non-invasive measurements*. Each leads to a possible inconsistency: In non-invasive measurements, the observer is certain of the superobserver's measurement outcome while the superobserver's physics predicts multiple possible outcomes. In invasive measurements the superobserver can be certain of his measurement outcome while the observer predicts non-zero probabilities for all possible outcomes.

I argue that in the case of non-invasive measurements, the perspectivalist avoids difficulty by denying that the observer's result has any impact on the physics experienced by the superobserver. Consistency is then maintained between them by looking to the unitary evolution of the superobserver's measurement. This response leads to a detailed discussion about the metaphysical commitments of the perspectival approach. Here I argue the perspectivalist must accept one surprising result – there is a significant divorce of fundamental ontological states from physical dynamics.

Turning to invasive measurements, I argue that the concern here is entirely misplaced. Arguments that raise worries about invasive measurements assume the observer should describe herself to be in a quantum state of having observed her measurement outcome when predicting the superobserver's measurement results. I argue that this is incorrect. Rather, I explain that it is impossible for any observer to know her quantum state and so she should never describe herself as being in any quantum state at all, let alone use such a description to make predictions about a superobserver's measurement.

To conclude, I explain how the perspectivalist responds to concerns raised about entanglement and the possibility of action at a distance. Combining this with the results above brings into focus how the perspectivalist may develop a consistent, single-world picture of quantum mechanics.

A GROUNDWORK FOR PERSPECTIVAL QUANTUM MECHANICS

by

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For my mother, Dr. Terry Nan Tannenbaum.

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Table of Contents

Chapter 1: Preliminaries

In 2016, a manuscript draft by Frauchiger and Renner [1] began circulating through the foundations of quantum mechanics community. It was provocatively titled, "Single-world interpretations of quantum theory cannot be self-consistent," and claimed to demonstrate that no theory could consistently hold that quantum measurements result in single outcomes while also maintaining the universality of unitary evolution. A later version of this manuscript [2] would be published two years later making a very different claim. Here, consistency, single outcomes of measurement, and universal unitarity are all expressed in terms of agents' "certainty" of quantum states and measurement predictions.

Together, both the original manuscript and its published version have had an interesting impact on quantum foundations. They've inadvertently brought a family of theories into the spotlight that had previously seen relatively little attention. These theories, which I will call *perspectival*, have been called by a number of names, including "neo-Copenhagen", "neo-Bohrian", "subjective collapse", and "relational". They are united in claiming that the introduction of some sort of observer-dependence permits us to explain how single outcomes can occur in a universe that evolves unitarily.

The term "perspectival" was suggested to me by Matthew Leifer. It is meant to best capture the fundamental position that quantum mechanics does not offer observer-independent descriptions of system states or evolutions. This is not to say that quantum mechanics is 'subjective' in the sense that there is not an objectively correct state description or evolution that should be used by (or for) a particular observer. Rather, the perspectival approach explains that quantum mechanics must be applied from a single perspective, which can be thought of as a measurement context for the moment. Various theories that fall under the perspectival umbrella then aim, at least in part, to explain away possible 'inter-perspectival' conflicts – disagreements that can appear across multiple perspectives. Part of the difficulty of this project, of course, is that unitary evolution seems to preclude the existence of single outcomes, and so these theories require a significant amount of work to detail their physical and metaphysical positions. This dissertation offers just a small piece of this work.

In much of what follows, I focus on two central problems that face the perspectivalist. These problems are raised by considering *encapsulated measurements* – measurements that involve an observer and a superobserver.[1] I focus on these cases because they are probably the simplest ones in which the perspectivalist must deal with the possibility of inconsistencies appearing between two perspectives. (Note that theories may differ on what counts as a perspective. Some, for example, may claim that only sufficiently complex systems can be treated as

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[1] Wigner was perhaps the first to raise the possibility of such measurements in 1961 [3] with what has come to be known as the *Wigner's friend* thought experiment, though one could easily argue that concerns relating to encapsulated measurements date back to Schrödinger's cat thought experiment [4].

observers and, therefore, be said to have a perspective in any relevant sense. I will discuss the merits and difficulties of such a view below, but I wish to focus primarily on cases where this question does not come up. In the case of encapsulated measurements, we are concerned with two systems that are clear cases of observers – two macroscopic experimenters.)

I begin by laying out what I take to be the foundational claims of the perspectivalist position. These will not be theory-specific insofar as I do not adopt any particular perspectival position. Following this I lay out the worries that arise from considering encapsulated measurements. I divide these into two categories, one of which follows from what I will call *invasive* measurements and one of which follows from *non-invasive* measurements. (This distinction between invasive and non-invasive measurements, which will be described in detail below, derives from the standard use of these terms outside of the quantum context.) I will then argue for what I take to be the strongest perspectival response to each.

First I will consider the concern that is raised from non-invasive measurements. Here it appears that the perspectivalist is forced to admit that the observer and the superobserver might observe contradictory outcomes of their respective measurements. I explain how the perspectivalist can avoid this while holding the Born rule probabilities to be 'genuine' (and non-epistemic) despite the fact that the superobserver's measurement result must be correlated with the observer's. This explanation will rest only the foundations of the perspectival approach outlined below, though this will admittedly feel somewhat unsatisfactory under any philosophical scrutiny. As such, I will then strengthen the approach, perhaps surprisingly, by looking by looking to Lewis's theory Humean supervenience. Although Humean supervenience is typically seen as incompatible with quantum mechanics [5, 6, 7], I explain that the conflict does not apply to the perspectivalist. This is because, following Bub [8, 9], she must understand quantum mechanics to be a *probabilistic*, not *representational* theory. Using the theory as a guide then, I discuss the possible ontological and nomological models available to perspectivalism. As I show, this leads to some surprising (but entirely consistent) constraints on the perspectivalist's metaphysics. Specifically, she is all but forced to take the fundamental ontology of the universe to be near classical (if not classical), despite the fact that its governing dynamics is quantum. Although this sounds quite exotic, it presents a coherent picture that can ground the perspectival theory.

Having done this, I will then turn to look at the worry of invasive measurements. The difficulty here is the one leveraged by Frauchiger and Renner: allowing an observer to predict the outcomes of a superobserver can lead to contradiction. Here I will explain that the perspectivalist's position is quite simple: she must deny that a system can describe itself as being in a quantum state. This is partially inspired by Lazarovici and Hubert's Bohmian response to Frauchiger and Renner, and so after reviewing their argument I will explain how it can be adapted to the perspectival position. As the Bohmian motivation will not do for our purposes, I will also explain how the claim might be defended in the perspectival framework by generalizing Breuer's proof against self-measurement.

Finally, I will conclude by with a brief discussion that cannot be neglected, which is how the perspectivalist can address entanglement and apparent action at a distance. Here I will show that everything needed to deal with cases of apparent non-local action already appears in responses to the issues raised by encapsulated measurements.

1.1 The perspectival position

Just as there is no formal or unified "Copenhagen interpretation", there is not a single perspectival theory of quantum mechanics. Rather, there are a number of (often conflicting) theories and results that fall under the umbrella. These include, for example, Rovelli's relational quantum mechanics [10], Healey's pragmatism [11, 12], and Giacomini *et al*'s quantum reference frames [13]. Rather than describe how each individually might respond (or fail to respond) to the problems that arise from encapsulated measurements, I will instead describe what I take to be the strongest general perspectivalist position.

The goal of the perspectival approach is to allow for quantum measurements to result in single outcomes while simultaneously maintaining that unitary evolution is universal. For example, if we consider the case of an observer, Alice, conducting a measurement on a quantum system, and a superobserver, Wigner, who will measure Alice, the perspectivalist wishes to explain that Wigner can and should treat Alice as evolving unitarily until he measures her, despite the fact that her measurement has a single outcome.[2] This is why the approach is

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[2] Note that the distinction between "observer" and "superobserver" is almost entirely artificial and carries no argumentative weight. Were Alice not isolated it would not be obvious at all which to call the observer and which the superobserver. I will not discuss this in detail here, but it is worth emphasizing that there is nothing special assumed about Alice and Wigner's relationship to one another.

called perspectival, of course. From Alice's perspective, she has observed a single outcome (and a break in unitarity), while from Wigner's perspective this is not the case.

It is worth offering a brief note about what is meant by 'perspective' here. The term does not represent a unique formal object, and this is because its formalization, if offered at all, will depend on details of the theory developed. For example, Giacomini and Brukner [13, 14, 15] might identify perspectives with quantum reference frames. Alternatively, one might define perspectives information-theoretically, for example in a Rovelli-style relational theory [10]. Moreover, there may be significant conflicts between how perspectives are described across theories. For example, Rovelli explicitly takes all systems (and all interactions) to be equivalent. (Thus, there are not special systems that can be considered observers, and not special interactions that can be considered measurements.) As such, in his theory it would make sense to speak of even elementary particles as having perspectives. However, Bub avoids discussion of single outcomes of interactions between elementary particles and may reject their having perspectives to consider at all.[3] For the purpose of investigating the general perspectival approach then, it will be best to think of perspectives less formally and more pragmatically. They can be understood as generalizing what is often called a *measurement context*: They include an observer who will experience single outcomes of measurements on quantum systems, though they do not identify a unique measurement basis (as measurement contexts often do) nor must the measurement actually occur.

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[3] This has been expressed in personal conversation and will be discussed in detail below.

For example, if we consider Alice measuring a qubit, we can speak of the possible measurements that may be conducted in her perspective and the possible single outcomes that might result (whether or not she makes any measurement at all). If she does make a measurement, then we can also speak about the outcome that actually does result. However, from Wigner's perspective, Alice and her qubit will appear as quantum systems and her measurement will be described as a dynamical process that unitarily entangles them together.[4]

Given these details then, we can start to position the perspectivalist approach in the 'quantum interpretations' landscape. In characterizing how any theory fits in this landscape it is difficult not to be reminded of Bell's claim: "Either the wave function, as given by the Schrödinger equation, is not everything, or it is not right." [16, p.201]. Hidden variable theories assume the quantum state is incomplete, of course, where dynamical collapse theories claim its dynamics is incorrect. As Wallace explains, the "Everettian move" is to reject Bell's claim altogether and accept quantum mechanics to be both correct and complete. [17, p.210]. In this sense, the perspectival approach is an alternative to Everett. It too makes the Everettian move but aims to do so without introducing many worlds or merely emergent classical histories.

To achieve this, the approach must reject the two 'dogmas' of quantum

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[4] One might be concerned here that we can define perspectives other than Alice's in which her measurement will appear to have a single outcome. For example, this may be the case if we consider the perspective of Alice's measuring device. I will address this in more detail in the discussion of invasive measurements below, but for the moment allow me to treat this case as merely a fine-graining of Alice's perspective. (After all, Alice will be interacting with the measuring device, which in turn is the system interacting with the qubit. It is not the case that Alice interacts with the qubit independently of the device.)

mechanics identified by Bub and Pitowsky[5] :

> The first dogma is Bell's assertion (defended in [19]) that measurement should never be introduced as a primitive process in a fundamental mechanical theory like classical or quantum mechanics, but should always be open to a complete analysis, in principle, of how the individual outcomes come about dynamically. The second dogma is the view that the quantum state has an ontological significance analogous to the ontological significance of the classical state as the 'truthmaker' for propositions about the occurrence and non-occurrence of events, i.e., that the quantum state is a representation of physical reality. [20, p.438].

The first of these dogmas includes two points which are worth teasing apart. The first is whether measurements are introduced as primitive, and second is whether they are "analyzable" dynamical processes.[6] Bell seems to note both of these points individually, explaining that "[t]he first charge against 'measurement', in the fundamental axioms of quantum mechanics, is that it anchors there the shifty split of the world into 'system' and 'apparatus'. A second charge is that the word comes loaded with meaning from everyday life, meaning which is entirely inappropriate in the quantum context. When it is said that something is 'measured' it is difficult not to think of the result as referring to some pre-existing property of the object in question." [19, p.34] Thus, I take whether measurement

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[5] Pitowsky first raises these as 'dogmas' in his [18].

[6] The distinction is related to the 'big' and 'small measurement problem' distinction that follows in [20].

is primitive to be a matter of whether or not there is a fundamental delineation between classical (or measuring) and quantum (or measured) systems, but this is a distinct question from whether we demand that the physical interaction of measurement be fully formally describable. Bell considers this second question in terms of how quantum measurements seem to diverge from classical ones, but we can generalize his point in Pitowsky and Bub's terms: It is a matter of whether the theory provides a detailed, or analyzable measurement dynamics.

Taking these points independently, then, we can imagine four positions – some of which will be much more tenable than others! First there is, for example, the Everettian approach, which adheres to the dogmas. Second, we can imagine a theory that introduces measurements as primitive but also analyzable. That is, it is logically possible to introduce special dynamics that captures the physics between primitively delineated classical and quantum systems. This may be one way to characterize dynamical collapse theories, for example. Third, a theory might accept primitive measurements but reject them as dynamically analyzable as Bub and Pitowsky suggest. This seems to characterize the various theories that fall under the (received) "Copenhagen" umbrella. Finally, a theory might deny that measurements are primitive but also deny that they must be analyzable. This is where I take the perspectivalist to fall.

This might seem surprising. It appears that the perspectivalist should embrace a primitively defined notion of 'measurement'. However, I think this places an undue burden on the perspectival approach. Introducing a primitively privileged type of interaction seems to demand answers to a number of questions that the theorist is not (or at least, should not be) prepared to answer: How are classical systems distinguished from quantum ones? Does a classical system 'become' quantum if it will be measured? etc. A far easier route for the perspectival approach is to reject that measurements must be defined primitively by noting that they need not be defined at all. That is, the perspectivalist can explain that quantum mechanics is theory that is used to predict everything *up to* a measurement. Quantum probabilities, as Bub says, "cash out in terms of 'what you'll find if you measure'." [8, p.3]. In this sense, the perspectivalist does not need any theoretically primitive delineation between the classical and the quantum. Rather, the theorist explains that it is mistaken to think of the theory as providing anything other than the probabilities of what will occur when 'you' (qua the system from whose perspective the theory is applied) interact with the system being described.

Underlying this is the Bohrian observation that "in each [measurement context] some ultimate measuring instruments, like the scales and clocks which determine the frame of space-time coordination. . . must always be described entirely on classical lines, and consequently be kept outside the system subject to quantum mechanical treatment." [21, p.14]. To speak of a measurement on a quantum system is to speak of an event *observed by a system that is necessary excluded from the theory*. The perspectivalist's job, in a sense, is to explain how this observing system can also be part of the theory when applied from the perspective of a system that observes *it*. To understand how this can begin to work, we need to look to the second dogma – that the quantum state is an 'ontological truthmaker' for proposition about which events do and don't occur.

Bub and Pitowsky reject the second dogma to explain that "Hilbert space [is] a new kinematic framework for the physics of an indeterministic universe, in the sense that Hilbert space imposes kinematic (i.e., pre-dynamic) objective probabilistic constraints on correlations between events." [20, p.438]. This has been further expounded in Bub's recent responses to Frauchiger and Renner [8, 9]. Here he explains that in order to maintain single outcomes and the universality of unitary dynamics, we must take quantum mechanics to be *probabilistic* rather than *representational*.[7] The quantum state is understood as "a bookkeeping device for keeping track of probabilities and probabilistic correlations between intrinsically random events." [8, p.4]. It is worth qualifying what is meant by 'bookkeeping' here. As Bub explains, the quantum world is fundamentally non-Boolean (in that it does not admit of a complete set of propositions than can be consistently assigned truth values). Hilbert space provides us with the kinematics for how this non-Boolean world manifests in any given measurement context. The measurement requires the quantum system to provide truth-values to a set of propositions that consistently form a Boolean subalgebra determined by the observable being measured. This probabilist route seems to be precisely the one that the perspectivalist must take. In order to maintain that measurements are not dynamical we cannot hold the quantum state to be representational (while also maintaining

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[7] As James Mattingly has raised in conversation, it is worth specifying that Bub's argument only rejects theories that take the quantum state to represent an *observer-independent* underlying state. Mattingly is currently developing a "single-user" quantum interpretation in which the quantum state *is* representational of the state of a system relative, but only relative to a 'user'. Such a theory is entirely consistent, but note that it does not concern itself with solipsistic worries as I do here. In what follows, "representationalism" should be understood as excluding theories like Mattingly's.

the universality of unitary dynamics). Such a combination will lead directly to solipsism or outright contradiction given the concerns raised by Frauchiger and Renner (as well as the worries I raise below).

This shift from representationalism to probabilism is precisely where the perspectivalist's 'Everettian move' differs from the many-worlds theorist's. While both claim that quantum mechanics is correct and complete, what the Everettian means by "complete" is very different from what the perspectivalist means. The Everettian takes the wave function and Schrödinger dynamics to provide a complete and correct representational description of the ontological state of the universe. The perspectivalist takes them to provide complete and correct predictions for an observer who measures a quantum system.

There are some questions that this type of position will raise immediately. The two that perhaps first come to mind are (1) Where do the Born probabilities come from? (Or relatedly, what is the true ontological state of a quantum system?) And (2), Does this force the perspectivalist into instrumentalism? As I will be discussing the ontological and nomological models available to the perspectivalist below I will leave detailed discussion of these until then. It is worth noting here, though, that the perspectival theorist may justifiably relegate some of these questions to the metaphysician. For example, questions about the 'source' of the Born probabilities might be seen as simply outside the scope of physics. That is, it might be explained that quantum mechanics provides the correct fundamental laws of nature and questions that ask "why *these* laws?" are not ones that physics is meant to answer. This is not to say that these questions are not worth considering, of course! (Indeed, I consider them in §3.4 and §3.5 below). I wish only to note that we should be careful in what follows to avoid demanding explanations from the perspectivalist that wouldn't be demanded of any other physical theorist.

Having established all this then, it will be helpful to list a few fundamental claims or central tenets that seem to define the perspectival approach. These are not meant to be axiomatic insofar as they are not independent of one another, nor are they claimed to be logically sufficient for all that is to follow. Rather, I provide them to help present the clearest picture of the perspectivalist starting point in advance of the more detailed position that will be developed below:

1. **Measurements result in single outcomes.** This is not a claim about the mere appearance of single outcomes (as would be accepted for example, by even Everettian mechanics). Rather it is a claim about what truly happens when an observer measures a quantum system – there is a single result, not merely the illusion of a single result, and certainly not a branching event the sees every possible result occur on various branches. (Of course, it will be the case that the result of a measurement may only be available within the perspective in which the measurement occurs.)

2. **Quantum mechanics is the correct and complete way to predict the outcome of measurement in any given perspective.** This is one way that we might express the perspectivalist 'Everettian move'. Given that we take quantum mechanics to be probabilistic, this makes explicit that the Born probabilities, as calculated from some perspective, are *the* correct physical predictions for measurements in that perspective. They represent the chances of possible outcomes that may result in

that perspective.[8]

3. **Unitary dynamics are universal.** Although measurements will result in a single outcomes, the physical interaction in a measurement should be described as a unitarily entangling process from any other perspective. The normative 'should' here reflects the fact that doing so will provide the correct predictions for any measurements that might be made upon the entangled systems. That is, failing to do so is empirically inadequate. Note that this does not require such a measurement to actually occur. Unitary evolution is not contingent on the existence of some future measurement context. Rather, the perspectivalist explains that the true fundamental dynamics of the universe is unitary, and so it is always applicable.

4. **Quantum mechanics is not representational. It is probabilistic.** As described above, the perspectivalist does not take the underlying ontological state of the universe to be the wave function. (Nor does she take the underlying ontological state of any subsystem of the universe to be its portion of the universal wave function or any quantum state.) What the quantum state does represent is the dynamical evolution of probability distributions of classical outcomes–in other words, it represents 'what will happen if you measure', and how this evolves in time.

There are, of course, further possible claims that individual theories may add

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[8] There is, in fact, an assumption being made here. It may be the case, once we are able to actually perform encapsulated measurements, that we discover we cannot treat an isolated system of some sufficient complexity as evolving unitarily. (Of course, this would demand that we revisit quantum mechanics generally.) Until we have evidence to the contrary, however, the perspectivalist assumes that quantum mechanical predictions will apply at all levels of complexity as long as coherence is maintained.

to this list, some of which I have mentioned or alluded to above. (For example, there is the question of what counts as an observer.) However, I see these claims as theory-specific. Although I will discuss some of these claims in what follows, I do not include them in categorizing the general perspectival position.

1.2 The difficulties of encapsulated measurements

Having outlined the perspectival position, we can now move on to describing the difficulties I wish to discuss. The obvious types of problems that will arise (and which I will deal with here) involve potential conflicts that appear between perspectives. What I wish to demonstrate in this section is how these types of concerns come about from very simple considerations about encapsulated measurements. I will first differentiate between *invasive* and *non-invasive* measurements and then characterize the difficulties that each raises.

My use of 'invasive' and 'non-invasive' roughly follows their usage elsewhere in discussions of quantum measurement. However, I will introduce somewhat non-standard (and more formal) definitions of the terms. Typically (in both quantum and classical contexts) a measurement is considered to be invasive if it changes the state of the system being measured. Conversely, a non-invasive measurement is one that does not change its state. For example, Leggett and Garg describe non-invasive measurements as those that "determine the state of the system with arbitrarily small perturbation on its subsequent dynamics." [22, p.857]. Similarly, as Knee explains about quantum measurement, "the unavoidable back-action in a projective measurement, where the state is updated to an eigenstate of the measured observable, is invasive." [23, p.56]. This distinction is troublesome for the perspectivalist, however. The reason for this is simply that whether or not the measurement will change the state of the system being measured will depend on the perspective considered. An example will help clarify this.

Say that Alice is in an isolated lab. She performs a computational basis measurement on a qubit that begins in the $|+\rangle$ state and obtains the result $|0\rangle$. Wigner, who is able to perform measurements on Alice's lab, treats Alice (and everything in the lab) as evolving unitarily.[9] Thus, when Alice's measurement is completed, he treats the lab as having evolved to the state $|A+\rangle = \sqrt{1/2}(|A0\rangle + |A1\rangle)$ (ignoring the relative phase for the moment) where $|A0\rangle$ and $|A1\rangle$ correspond to states of the lab where Alice has observed $|0\rangle$ and $|1\rangle$, respectively.[10] We'll consider two possible measurements that Wigner might make. The first is in the basis $\{|A+\rangle, |A-\rangle\}$ (where $|A-\rangle = \sqrt{1/2}(|A0\rangle - |A1\rangle)$). The second is a measurement in the basis $\{|A0\rangle, |A1\rangle\}$. For the sake of brevity, I'll call these the +/- and 0/1 measurements, respectively, and I'll refer to Alice as 'shorthand' for her entire lab (unless made otherwise explicit).

Looking to Wigner's perspective then, Alice is in the $|A+\rangle$ state prior to his measurement and so he is certain of the +/- measurement outcome while both

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[9] Strictly speaking, what is relevant is that Wigner is able to measure everything that has become entangled with the qubit, not that Alice's lab is isolated. I follow standard practice in speaking of isolated labs. See, for example, [2] and [24], the latter of which equivocates between these two qualifications.

[10] In other words, if q is the qubit, a is Alice, and e is the environment of the lab, then $|A0\rangle = |0\rangle_q \otimes |0\rangle_a \otimes |0\rangle_e$, where $|0\rangle_a$ is the state of Alice having observed $|0\rangle$ and $|0\rangle_e$ is the state of the environment of the lab having becomes entangled with Alice's $|0\rangle$ observation.

outcomes of the 0/1 measurement are equiprobable. Now a 'textbook' quantum theory, or more specifically a theory that adopts the eigenstate-eigenvalue (E-E) link,[11] will explain that the +/- measurement is not invasive. After all, Alice begins in the state $|A+\rangle$ and ends in the state $|A+\rangle$. Conversely, the 0/1 measurement is necessarily invasive, as Alice begins in $|A+\rangle$ but must end in either $|A0\rangle$ or $|A1\rangle$.

The perspectivalist, of course, will deny the E-E link in at least the following fashion: It is possible for there to be a determinate value of Alice's measurement (in the sense that she has observed a definite outcome) while Alice is in an eigenstate of Wigner's +/- measurement (in the sense that Wigner correctly describes her as having evolved unitarily to a state that doesn't correspond to her having observed a definite outcome). This suggests that from Alice's perspective the +/- measurement is necessarily invasive, as it will force her into either the $|A+\rangle$ or $|A-\rangle$ state, neither of which correspond to her measurement having resulted in the single outcome that was actually obtained. It is likely obvious how this can become even more difficult if we consider the case where Alice's and Wigner's measurements have three or more possible outcomes.

One might arrive at the same conclusion without the E-E link, but my point here is not to consider how best to characterize Wigner's measurement. In fact, I raise this observer-dependence in differentiating invasive from non-invasive measurements not because the manner in which we differentiate the two will be important, but rather because it won't! The definitions that I will employ for these

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[11] Wallace explains in [25] that the E-E link should not be attributed to 'orthodox' quantum mechanics, assuming that orthodoxy is determined by what physicists *actually do*. I agree, and so use 'textbook' to refer to the received view in an introductory quantum physics classroom.

terms serve only to point out particular types of difficulties that arise – they do not do any work beyond this. It is the difficulties that the perspectivalist responds to, not how types of measurements are characterized or differentiated. Moreover, it is not the case that the perspectivalist position that I describe suggests a physical (or metaphysical) distinction between these types of measurement. Rather, what I will present is a single position that responds to the problems raised from each.

Having made this clear then, I wish to describe invasive and non-invasive measurements in the following fashion: Say an observer S_1 in an isolated lab makes a measurement on some system s in a basis $\{|\pi_i\rangle\}$ which results in the outcome $|\pi_j\rangle$. Another system S_2 treats the lab as evolving unitarily and is able to perform measurements on it in any basis. If $|S_1 k\rangle$ are states of the lab wherein S_1 has observed the outcome $|\pi_k\rangle$, then an invasive measurement will be a measurement in any basis that does not include $|S_1 j\rangle$. Conversely, a non-invasive measurement will be a measurement in any basis that does include $|S_1 j\rangle$. [12]

The way to think about this distinction is to consider whether S_2's measurement must result in an outcome incompatible with S_1's observation. For example, if Alice observes $|0\rangle$, both possible outcomes of the +/- measurement represent

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[12] It may seem unnecessary to include both S_1 and S_2 here – I could simply define invasive and non-invasive in terms of whether a measurement includes an eigenvector corresponding to the state of the system being measured. However, I don't want to accidentally make any assumptions about which systems can and can't be said to be observers, nor about the ontological state of microscopic systems. (These will both be further discussed in the sections that follow.) By defining these in terms of systems that are explicitly taken to be observers I avoid, for example, demanding an electron observes single outcomes. The cost of this is that a measurement on an electron may not be definable in terms of its invasiveness (assuming the electron is not taken to have a perspective). Although this may seem worrisome at the moment, it is not a problem insofar as these definitions don't indicate any metaphysically or ontologically important distinctions.

superpositions of Alice having observed $|0\rangle$ and $|1\rangle$ and so the measurement is necessarily invasive. The 0/1 measurement, on the other hand, might be understood as Wigner merely learning what Alice has seen. In this sense, you might think of the 0/1 measurement as being roughly equivalent to a classical measurement in which Wigner opens the door to Alice's lab and asks her what she observed. Such a measurement is intuitively non-invasive insofar as Wigner only needs to gather information from Alice's lab – no change in the lab needs to occur. This is not generally true for non-invasive measurements though. If S_2's measurement has a dimensionality greater than two then there are an infinite number of non-invasive measurements that can be made, only one of which might be equivalent to 'opening the lab door' (and only so in the case where S_1's measurement is of the same dimensionality as S_2's).[13] For the most part I will only consider cases where Alice's and Wigner's measurements can only result in one of two possible outcomes, though I will return to comment on the more general case as necessary.

With these definitions we can consider the difficulties that follow. Both result from discrepancies that appear between Alice's and Wigner's predictions about Wigner's measurement. Consider first the case of invasive measurements. As mentioned above, Wigner is certain that a +/- measurement will result in $|A+\rangle$. However, if Alice were to make a prediction about Wigner's measurement under

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[13] One might worry that in the case where Alice's and Wigner's measurements have dimensionality greater than 2 it cannot be known in advance whether a measurement will be invasive or not without knowledge of Alice's outcome. This worry is misplaced, however. We are concerned with conflicts between Alice's and Wigner's perspective, which can only be considered from the theorist's 'god's eye view' with access to both perspectives. As mentioned above, the perspectivalist position does not change based on the type of measurement made. Thus, whether or not Alice or Wigner can know whether Wigner's measurement is invasive doesn't impact the perspectivalist position at all, and in fact, only reinforces that this distinction is somewhat artificial.

the assumption that she has 'collapsed' into the state $|A0\rangle$, the Born rule dictates that both $|A+\rangle$ and $|A-\rangle$ outcomes are equiprobable. This discrepancy can be seen at the heart of the Frauchiger-Renner thought experiment [2] (as discussed by Salom [26]). (The Frauchiger-Renner argument will be further discussed in §4.2 below.)

Looking to the case of non-invasive measurement, here we imagine Wigner will perform the 0/1 measurement. As he describes Alice as being in the $|A+\rangle$ state, he will predict that both outcomes are equiprobable. Alice, on the other hand, will predict the result $|A0\rangle$ with certainly given her measurement result.

In both cases, if we take the Born probabilities calculated to be representative of what might actually happen then the discrepancy between Alice's and Wigner's predictions seem to demand that contradictory outcomes are possible.[14] This has been explored perhaps most recently by Baumann and Wolf [27][15], who demonstrate that discrepancies resulting from the +/- measurement case can lead to what they call *scientific contradiction* – conflicting pieces of classical information at a single spatiotemporal location. In other words, the discrepancy is not isolated to comparisons between Alice's and Wigner's perspectives. Rather it is possible to build a contradiction that is available to a single observer. In their case, the conflict arises by allowing Alice to communicate her predictions to Wigner (in a fashion that maintains the coherency of her lab's state). The same protocol will not work for the 0/1 measurement case, as Alice's prediction would reveal

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[14] One might also take the difficulty to mean that either Alice's or Wigner's prediction are incorrect. However, such an interpretation clearly denies our central claim that quantum mechanics is complete and correct and so I will not consider it here.

[15] Their full argument will be discussed in §4.1.

her measurement outcome. However, if we allow Wigner to communicate his predictions to Alice, then a parallel argument would apply. [16]

Note that this asymmetry – whether it is Wigner or Alice who must communicate to the other to produce a scientific contradiction – does not generally distinguish invasive from non-invasive measurements as I've defined them. For example, if Wigner were to make a measurement in the basis $\{(\sqrt{3}/2\,|A0\rangle + 1/2\,|A1\rangle), (1/2\,|A0\rangle - \sqrt{3}/2\,|A1\rangle)\}$, this would be invasive. However, Alice's predictions for such a measurement would be dependent on her measurement result, and so relaying this prediction to Wigner would necessarily decohere her into Wigner's environment just as in the case of her prediction for the 0/1 measurement. As I have defined invasive and non-invasive measurements, the distinction lies in whether Alice has reason to predict one of Wigner's measurement outcomes with certainty. In non-invasive measurements she does, and she doesn't in invasive ones.

This characterization of the distinction between the two cases is useful in explaining why I define invasive and non-invasive measurements in this way. The perspectivalist is committed to saying that there are single outcomes for both Alice's and Wigner's measurements. But this doesn't entail a commitment to claiming that Alice should (or can) use her outcome to predict the outcome of *any* measurement that Wigner might make. Indeed, this is precisely what I will deny in my discussion of invasive measurements. Before getting to these cases though,

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[16] In fact, Baumann and Brukner have argued as much in their recent [28]. It is not obvious that this reversal of Baumann and Wolf's protocol is physically possible, but this is tangential to the point here. I will discuss this further in §4.3.2.

I will first look to the difficulty of non-invasive measurements. Here a conflict arises without any assumptions about how Alice predicts Wigner's outcome, but we will see that the perspectivalist's response demands a significant metaphysical discussion.

Chapter 2: Non-invasive measurements

Cases involving non-invasive measurements are somewhat easier to picture than those involving invasive ones as they don't ask us to consider measurements in bases containing superpositions of Alice's results. Despite this simplicity though, we will see that the perspectivalist's job here is difficult compared to the case of invasive measurements. The reason for this is that in the case of invasive measurements the perspectivalist will simply deny a premise that leads to trouble. Here, however, she accepts the premises that lead to the apparent contradiction and must explain how trouble is avoided – and to do so she must carefully walk a fine line between complete instrumentalism and extreme solipsism. This turns out to have quite strong consequences for her metaphysics and so these cases turns out to be central in laying out the perspectivalist's philosophical commitments.

2.1 Diagnosis

Consider again the case where Alice makes a measurement and observes $|0\rangle$, followed by Wigner measuring Alice in the $\{|A0\rangle, |A1\rangle\}$ basis. I have likened this to Wigner opening the door to Alice's lab to ask her what she has observed.

Under this description Alice doesn't need to make any unusual predictions to know what will occur when Wigner knocks (in her perspective). She will open the door and tell Wigner what she saw – no quantum mechanics needed!

It might seem worrisome that I am equivocating between a quantum measurement and this very classical interaction. After all, a quantum description of Wigner opening the door would be quite different from the classical one. (Notably, it takes far less time for Alice's lab state to decohere into Wigner's environment than it takes for Wigner to finish opening the door to ask Alice about her result. See §2.2.2.) But my point here does not rely on the details of the quantum description of the measurement at all, let alone on Alice decohering into Wigner's environment. This can be made clearer by changing the measurement protocol to simplify the quantum interaction involved: Imagine that Alice and Wigner agree that after completing her measurement Alice will send a polarized photon from within her (otherwise isolated) lab to encode her result: $|h\rangle$ for $|0\rangle$ and $|v\rangle$ for $|1\rangle$. Wigner will measure just the photon in the $\{|h\rangle, |v\rangle\}$ basis as soon as it is emitted to learn the outcome of Alice's measurement. Of course, he will then describe the lab as being in a coherent $|A0'\rangle$ or $|A1'\rangle$ state (where these states now represent the state of the lab less the emitted photon). If we consider this protocol from Alice's perspective, again it doesn't seem like quantum mechanics is truly necessary for her to predict what Wigner will observe insofar as no interaction here seems to depend on a non-classical description of events. She observes an outcome and encodes it in a photon that she sends to Wigner. Wigner then 'decodes' her result from this photon. From her perspective, the photon might as well be a piece of paper that reads “0” or “1”.

The measurement is very different from Wigner’s perspective, of course. In this protocol, Wigner will describe Alice’s lab and signal photon as evolving to a state $|A+'\rangle = \sqrt{1/2}(\,|A0'\rangle\,|h\rangle + |A1'\rangle\,|v\rangle)$. Applying the Born rule to describe the probabilities of the possible outcomes we find the problem, of course. If Wigner’s measurement appears non-quantum (and deterministic) to Alice, it seems like the fact that Wigner calculates a 50% chance of observing $|1\rangle$ indicates that the Born rule is providing merely epistemic probabilities. The perspectivalist, however, does not want to reduce Born probabilities to epistemic uncertainty. However, naïvely positing that these represent ‘genuine’ possibilities for Wigner seems to force us into solipsism. It implies that even when Alice observes $|0\rangle$ is it possible for Wigner to find that she is in the state $|A1\rangle$ (and thus has observed $|1\rangle$).[1] Thus, the task of the perspectival theorist here is quite daunting.

It is worth pausing here for a moment to consider the case when Alice’s and Wigner’s measurements are of higher dimensionality, just to demonstrate that nothing I will argue depends on the two-dimensionality of the observables considered. Say, for example, that Alice measures the z-spin of a spin-1 particle to observe possible results $|z_+\rangle$, $|z_0\rangle$, or $|z_-\rangle$. If Wigner measures Alice in the basis $\{|Az_+\rangle, |Az_0\rangle, |Az_-\rangle\}$ (using parallel notation to that above), then all is the same as in the case we just considered. However, say that Alice observes $|z_0\rangle$ and Wigner measures in the basis $\{|Az_0\rangle, \sqrt{1/2}(|Az_+\rangle + |Az_-\rangle), \sqrt{1/2}(|Az_+\rangle - |Az_-\rangle)\}$.

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[1] As noted above, this could also be understood as implying that one of their predictions is simply wrong. However, this would imply that quantum mechanics is incorrect, which cannot be the case here by assumption.

This case might feel like it should be very different from 'opening the door to Alice's lab,' as two of the measurement basis vectors don't at all correspond to states of Alice having observed a single outcome. The relevant question, though, is not whether the analogy holds. Rather, it is whether this scenario demands a quantum treatment by Alice to predict Wigner's outcome – and I maintain that it does not. Putting aside questions about how such a measuring device would physically appear to function from Alice's perspective, we can note that what it must do is determine whether Alice's measurement resulted in $|z_0\rangle$, and only if it didn't, distinguish between possible relative phases between the other 'branches' of the wave function.[2] This is not to say that the actual quantum measurement should be thought of as a two-step process, of course, but thinking of it in this fashion highlights that Alice's prediction of Wigner's outcome again doesn't seem to demand a quantum treatment. Think again of a parallel scenario where Alice emits a particle from her lab to encode her result (which here may simply be the same particle that she measures!). Alice can reason that, given her result and the measurement basis, she is simply 'telling' Wigner what she got, and this can be the case regardless of what she might say *had her measurement result been different*. That is, it may be that had she not observed $|z_0\rangle$ she would treat Wigner's measurement very differently, (this will be discussed in much more detail in my response to the problem raised by invasive measurements), but this is not problematic. Alice does not treat her measurement as a unitary evolution, and so nothing precludes

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[2] This is said without commitment to taking the wave function as representational, let alone any ontological commitment to branches.

its result from informing how she treats future measurements or interactions.

We can generalize this to non-invasive measurements of higher dimensionality quite easily. As long as Alice is predicting the result of a measurement whose basis includes an eigenvector corresponding to her having observed her actual result, Alice can be certain about the outcome while the Born rule provides non-zero probabilities for other possible outcomes in Wigner's perspective. What must be explained, then, is how the probabilities that Wigner calculates can be understood as indicating genuine possibility given that his result must be perfectly correlated with Alice's in order to avoid solipsism.

2.2 The perspectival response

I will provide the perspectivalist response to the case of non-invasive measurements as follows: First I will discuss how the Born probabilities can be understood as 'genuine' given that Alice seems to know the result of Wigner's measurement in advance. This will follow directly from the perspectivalist's central tenets, although it will demand a slight divergence from our intuitions (which will be further addressed in chapter 3). However, this treatment of the Born probabilities will offer no explanation for how it is that Alice and Wigner's results are correlated, and so this will follow. Here I will again show that the central tenets are enough to explain this without changing how we understand the Born probabilities at all.

2.2.1 Genuine probability

To address the 'genuineness' of the Born probabilities we turn back to the central claims of the perspectival approach. Recall that the perspectivalist holds that quantum mechanics is the correct and complete physical description of what will result from a measurement on any system. A direct consequence of this is that Alice's outcome, although a determinate event in Alice's perspective, cannot appear determinate in Wigner's perspective. More specifically, if quantum mechanics provides the best predictions that Wigner might make for his measurements of Alice, then given that determinate values for Alice's outcomes are incompatible with the $|A+\rangle$ state that Wigner uses to describe her, he cannot treat her as having observed a single outcome in his perspective. Of course, this also precludes Wigner from treating Alice as disjunctively having observed $|0\rangle$ or having observed $|1\rangle$. Neither disjunct is compatible with quantum predictions, as proven by well-known no-go results such as Bell's theorem [29] (and the Kochen-Specker theorem [30] in higher dimensions). In this sense, Alice's outcome 'does not exist' in Wigner's physics.[3] What I wish to press is that this is enough to maintain that Born probabilities are *genuine*.

To argue this properly we must at least clarify what is meant by 'genuine', as the term is hardly well-defined.[4] Despite this, it is quite ubiquitous in philo-

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[3] Some have raised concerns about speaking of "existence" in this manner while others have suggested it. I choose to speak of Alice's outcome being nonexistent for Wigner (or in his physics) whereby I specifically mean that his best physics precludes him from treating Alice as having observed a single outcome on pain of contradiction. Some further discussion regarding this follow in §2.2.1.2.

[4] There might be concern that I choose to speak of "genuine" instead of "objective" probabilities here. The choice is due to the fact that the meaning of "objective" can be easily confused with "inter-

sophical literature - especially in discussions of epistemic vs genuine necessity.[5] I do not wish to survey uses of the term here, first because such a project would surely take far too much time, and second because this is tangential to the task at hand. What we need for our purposes is some sense of 'genuine probability' that is adequately far from '(mere) epistemic probability' and sufficiently close to our intuitive concepts to satisfy the perspectival skeptic. I will argue here that such a sense is readily available given the central tenets above.

The epistemic is standardly contrasted with the metaphysical, and so a natural move may be to look to discussions of metaphysical possibility or necessity to understand how Born probabilities might be 'genuine'. This move sounds much easier than it is, however. As Glazier notes, "[t]he notion of metaphysical necessity... has been familiar since Kripke, yet there has been no shortage of controversy over how it is to be understood," [31, p.2] and I see no reason even to hope that the parallel discussion about metaphysical possibility would contain any fewer disagreements. Moreover, the waters get even murkier without a sufficiently detailed metaphysics[6] and although I will argue below that perspectivalism carries significant metaphysical commitments, we haven't yet a sufficiently detailed metaphysical picture to appeal to.

Thus, rather than starting from metaphysical possibility, I want to sug-

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perspectival" in the context of perspectivalism. All that I say here about 'genuine' probabilities applies equally well to 'objective' ones given an appropriate specification of objectivity in the perspectival context.

[5] For a list of some examples, see [31, §1].

[6] To clarify, even once a detailed metaphysics has been established, there remains questions about what is metaphysically possible. Most relevant to the discussion here is whether one ought distinguish between metaphysical and nomic possibility. (C.f. [32].)

gest a different and perhaps more straightforward approach. In the context of physics, genuine or objective chance is typically contrasted with determinism. The thought, of course, is that if physical laws fully determine the future there is no room for 'chancey' events. (See, for example, [33].)[7] Given this, an alternative to focusing on metaphysical possibility is to turn to the indeterminism that follows from taking quantum mechanics to be probabilistic. That is, if the Born rule describes chances of indeterministic events, then we already have enough to consider the Born probabilities to be 'genuine'.

Bub's (perhaps 'pre-perspectival') theory is very clear about indeterminism in quantum physics. As cited above, he and Pitowsky describe that "Hilbert space provides the kinematic framework for the physics of an *indeterministic universe*." [20, p.439, emphasis added]. This has been elaborated in [8, 9, 37, 38, 39] to explain that the Born probabilities represent outcomes of *intrinsically random* events. And again, this seems to be the correct position for the perspectivalist. Rejecting quantum mechanics as representational and maintaining that quantum mechanics is complete and correct from every individual perspective *just means* understanding it as providing the correct probabilistic predictions for what will be observed in that perspective. In other words, there is nothing physically available to Wigner – nothing he could do to Alice's lab while maintaining its coherence – that would allow him to improve on the predictions of quantum mechanics and the Born rule. The fact that Alice is able to make predictions that are unavailable

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[7] There are some attempts to retrieve objective chance in deteministic contexts, for example [34, 35, 36], but I do not wish to engage with this discussion here.

to Wigner does not change this fact. (We already know that what is available in Alice's perspective, namely her measurement outcome, is not available in Wigner's physics.) Moreover, should Wigner treat Alice as having observed one outcome, he can only 'do worse' to predict the outcomes of his measurement, generally speaking. In other words, he can acquire evidence *against* treating the Born probabilities as being merely epistemic (given sufficient resources). What this means though is that Wigner can, and should, correctly understand the Born probabilities as indicative of what he might get when he measures Alice, and this is all that is needed to explain how the Born rule probabilities are genuine: They are not epistemic, as Wigner's cannot 'do any better', and Wigner cannot physically treat Alice as being in a state in which her measurement resulted in a single outcome. [8]

Now this will surely fail to satisfy the skeptic. She will explain that what matters is not merely whether Wigner can improve his predictions about his measurement outcome. Rather, what matters is the fact that his outcome is predetermined by Alice's outcome. As such, unless we want to permit contradictory outcomes, the Born rule probabilities cannot truly represent 'what he might observe'. The problem with this is that it rests on an assumption that is precluded by the theory. That is, when the skeptic explains at this point that Wigner's measurement is predetermined by Alice's, she demands that we consider two perspectives simultaneously – both Alice's and Wigner's – and doing so represents a departure

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[8] It is worth noting that Demopoulos discusses a parallel view in [40]. Here he explains that quantum states provide the probabilities of *effects*. I will not address the view in detail here as (unlike Bub) Demopoulos takes this approach to be fundamentally instrumental.

from our physics according to perspectivalism. The difficulty, of course, is that we are strongly compelled to think that if Alice observed an outcome, it is simply an outright, non-perspectival *fact* that she observed that outcome. The outcome 'exists' for all systems in the universe (up to relativistic considerations, perhaps). But this is *precisely* what the perspectivalist denies when we say that quantum mechanics is complete and correct in every perspective. Again, we know very well from the Bell and Kochen & Specker theorems that if the theory is complete then Alice's measurement outcome must be indeterminate for Wigner.

2.2.1.1 Back to metaphysical possibility

At this point a skeptic who wishes to stand her ground might return to the question of metaphysical possibility and make the following claim: Granted, the Born rule provides 'objective' possibilities in this perspectival sense, but this neglects to consider the *metaphysical fact* that Wigner cannot observe $|A1\rangle$ when Alice has observed $|0\rangle$ (unless we permit solipsism or acknowledge that quantum mechanics is incorrect). In this sense the Born probabilities cannot represent 'genuine' possibilities.

The skeptic seems to have a valid point here. We tend to think of metaphysical possibilities as subsuming genuine possibility. It seems metaphysically possible, but not genuinely so, for pigs to gain the ability to fly tomorrow at 5:17pm, for example. If this is the case, then the skeptic can present the following argument:

1. If P is genuinely possible, then P is metaphysically possible.
2. $\therefore$ If P is not metaphysically possible, it is not genuinely possible.
3. It is not metaphysically possible for Wigner to measure $|A1\rangle$ when Alice has observed $|0\rangle$ (or vice versa).
4. $\therefore$ It is not genuinely possible for Wigner to measure $|A1\rangle$ when Alice has observed $|0\rangle$ (or vice versa).
5. The Born rule describes that it is possible for Wigner to observe $|A1\rangle$ when Alice has observed $|0\rangle$.
6. $\therefore$ The Born rule does not describe genuine possibilities.

But the perspectivalist reply here is quite simple: we haven't at all offered to provide an account of metaphysical possibility. Indeed, we've explicitly put this aside for the moment in order to get to an adequate account of why Wigner's probabilities may be genuine *given* that his result must be consistent with Alice's, and this is what has been provided: The probabilities do not represent epistemic uncertainty, as treating them as such leads to verifiably incorrect predictions via Bell's theorem, and they do represent physical possibility insofar as physical possibility is determined by physics! In Wigner's perspective it is physically true that he might observe that Alice's measurement resulted in $|1\rangle$ regardless of what has transpired in Alice's perspective. If it turns out that this leads to a result that conflicts with our intuitions about how metaphysical and genuine possibility are related (i.e., if it turns out that we show 2. in the above argument to be false), then so be it. This is a direct result of the fact that we have the ability to think about things beyond the scope of our physics, be they multiple quantum perspectives or porcine aerodynamics. There will be more to say about the perspectivalist's take on how metaphysical and physical possibility and necessity are related, but I will return to this only once we arrive at the metaphysical implications of the perspectival response to the difficulty of non-invasive measurements.

2.2.1.2 The (non)existence of Alice's outcome in Wigner's physics

Before continuing to look at how the perspectivalist explains the consistency between Alice's and Wigner's results, I wish to briefly further discuss what I have said regarding the nonexistence of Alice's measurement outcome in Wigner's perspective. The claim may sound preposterous when thinking about Alice's measurement. Indeed, we picture her as a very complex system – a person who experiences measurements as we do. Moreover, we can't appeal to Alice's isolation to write off our intuitions about her experience. As Wallace points out, "there is. . . every reason to think that the microscopic degrees of freedom of even an isolated system suffice to destroy coherence between macroscopic superpositions of that system's macroscopic degrees of freedom.. . . [F]or systems above quite small length-scales, coherent superpositions of states with macroscopically distinct positions rapidly become entangled with their environment." [41, p.81]. However, it is central to the perspectival theory that Wigner's (and our) attitude towards Alice should be just the same as the typical attitudes we hold about simple quantum systems.

It may help to clarify what this implies by considering a simple, textbook example. Consider sending an electron in the $|z+\rangle$ state into an isolated 'box'. Inside the box is, first, an x-spin measurement device that sends $|x+\rangle$ electrons in one direction and $|x-\rangle$ electrons in another, and second, a device that combines these two paths and emits the electron (and nothing else) from the box. Our standard treatment of this situation is as follows: The electron enters the box and passes through it in a superposition of both paths. It then exits the box in the superposed state, which can be confirmed by repeating the process multiple times and passing each output electron through a z-spin measurement device. In every case the electron will exit the box and be measured to be in the $|z+\rangle$ state. Now this is not meant to be surprising. Rather, I wish to draw attention only to the fact that a standard explanation of the final z-measurement statistics must explicitly deny treating the electron as if it had gone through one path or the other and this is simply because each path would lead to a 50% chance of the z-spin measurement resulting in $|z-\rangle$. When we consider Wigner's description of Alice, the exact same is true, and this is *independent* of his describing Alice as having observed a single outcome in her perspective and of his being certain that his result will be perfectly correlated with hers.

It certainly seems foreign or exotic to say that a measurement result will be correlated with something that can't play a role within the physics that describes it, but this is unfortunately one of the clear results of quantum mechanics. Consider again the isolated box, and imagine that we include within it a device that monitors and records which path the electron takes before being emitted.

Quantum mechanics tells us that performing z-spin measurements on electrons emitted from the box would produce the same 100% $|z+\rangle$ results.[9] But, if we now consider making x measurements on the emitted electrons and comparing their results with the internal path-recording device, we would find that each of our measurement results would indeed be perfectly correlated with the corresponding internal record. Thus, we find that the x-spin measurement results are perfectly correlated with a variable that cannot be treated as having a determinate value. As we will see in §2.2.2, what is key is to recognize that the physical predetermination of Wigner's outcome (in Alice's perspective) can be separated from its correlation with Alice's.

2.2.2 Consistency from the universality of unitarity

Having established the Born probabilities to be genuine (in an appropriate sense, at least), my next task is to explain how inconsistency is avoided. And just as I argued that qualifying the Born probabilities as genuine follows from taking quantum mechanics to be complete and correct, I will show the same is true of inter-perspectival consistency. In this case, merely taking unitary evolution to be universal is enough to ensure that Wigner and Alice become entangled such that their measurement results are perfectly correlated. Before presenting this position, however, it is worth looking at alternatives that have been suggested recently by Drezet [42] and Salom [26].

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[9] The path-recording device is isolated, so it evolves unitarily to a superposition of recordings of each path.

Responding to Frauchiger and Renner [2], both Drezet and Salom argue that one path for Copenhagen-style approaches (which can fall under the umbrella of "perspectivalism") to deal with encapsulated measurements is to permit Alice's memory to be 'malleable.' Their suggestions are slightly different, and so I will present each of them in turn.

Although Drezet is mainly concerned with responding to Frauchigner and Renner from the Bohmian perspective, he discusses a suggestion attributed to Deutsch [43] to explain how a Copenhagen theorist might maintain consistency in the case I've described. This is to allow for (at least parts of) Alice's memory to be erased and rewritten when Wigner measures her lab. The suggestion straightforwardly avoids contradiction by permitting Alice's result to *change*. If Alice makes her measurement at time t_0 and observes $|0\rangle$, Wigner can measure her at time t_1 to observe that she 'has observed' $|1\rangle$. After Wigner's measurement, Alice will simply 'mis-remember' what she observed. Of course, 'Alice' stands in here for her lab and everything has become entangled with it, and so when we speak of Alice's memory being erased we mean all physical records of Alice's original outcome being 'rewritten'. In this sense, Alice doesn't mis-remember her $|0\rangle$ observation insofar as it is true at time $t_0 < t < t_1$ that she obtained $|0\rangle$ at t_0, but true at times $t > t_1$ that she obtained $|1\rangle$ at t_0. Aside from the fact that treating Alice and her lab this way may seem unpalatable (both metaphysically and ethically!), there is a significant difficulty with this approach.

Recall that I compared Wigner's 0/1 measurement to his opening the door to Alice's lab. As mentioned above, the analogy is weak. If we were to detail such a process, we would find that very shortly after the lab's isolation is broken (by Wigner's opening the door) it would decohere into the external environment – certainly much, much faster than Wigner could be finish opening the door, let alone ask Alice about her outcome and process her answer. (Wallace explains that Schrödinger's cat would remain in a coherent state for $\sim 10^{-35}$ seconds, for instance. See his [41, §3.5] for details of the calculation of the timescales involved.) As such, there is a very real sense in which, between Wigner's breaking the isolation and his learning about Alice's outcome, it is correct to say that Wigner's uncertainty about what Alice observed is indeed epistemic.[10] What we are truly concerned about when we discuss the encapsulated measurement is the point at which Alice's lab is no longer evolving unitarily in Wigner's perspective.[11] Recall the protocol in which Alice emits a photon to signal her outcome. Given this protocol, we can be slightly more accurate about the point at which unitarity is broken in Wigner's perspective (i.e. when Alice's state will decohere into his environment). This will be the point at which the emitted photon hits the polarizer that Wigner has prepared. Given this specificity, we can better consider what the Deutsch-Drezet approach entails.

In order to maintain that Alice's memory can be erased and rewritten, it must be that at the moment when the photon and polarizer interact there is a 50% chance that Alice's lab's state changes. This is highly problematic though. First,

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[10] In fact, Sebens and Carroll [44] pursue this line in their explanation for probability in Everettian mechanics.

[11] It is worth noting that I am treating Wigner in his environment as a single perspective. There are certainly cases where we would not want to do this – for example, when we are formally describing decoherence. However, this coarse-graining is not problematic in this context.

it seems to demand some kind of action at a distance, as the lab's isolation means that there is no way for anything to be communicated from the polarizer back into the lab to initiate this change.[12] Second, thinking about what this would require within the lab (given that we are taking Alice to have observed a single outcome prior to Wigner's measurement), it seems that we would either need to posit a purely spontaneous, almost 'magical' rearrangement of the particles inside the lab or we would have to imagine that Alice and her environment are 'rewound' and 'fast-forwarded' to a new state. Neither of these seem physical, of course. The first demands completely exotic and discontinuous dynamics.[13] The second would violate conservation laws given the lab's isolation, if not before and after the change than at least for any period in between.[14] In either case, this approach immediately implies that our physics is incomplete as it cannot describe such a change.

One remaining possible attempt to salvage the view might be to introduce retrocausal action into our physics. Thus, after the photon interacts with the polarizer, a signal is sent back to the time of Alice's measurement to determine Alice's outcome so as to ensure that it is consistent with what Alice's message communicates to Wigner. This possibility is indeed available, and is defended by Price [47, 48], for example, but will amount to the same outcome I will suggest

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[12] I will discuss action at a distance in more detail below (§5.1), but note that the response I suggest there will not help here. As will be explained, the perspectivalist can deny that apparent cases of action at a distance necessitate any non-local change to a system's state. However, such a change is assumed here.

[13] Recent results by Minev *et al.* [45] might suggest that the dynamics need not be discontinuous. However, even if this is correct, the dynamics involved are entirely exotic.

[14] One might appeal to the energy-time uncertainty relation to justify this, but it is far from clear that this is an appropriate interpretation of the relation. For some discussion see [46].

here at a much higher cost.

This retrocausal treatment is very similar to one of the options that Salom considers, but not the one I wish to focus on. His general position is different from the Deutsch-Drezet approach, and in some sense closer to the one I outline. Much as I explain that Alice's outcome doesn't exist for Wigner, he explains that we must deny the ascription of any subjective experience to Alice from Wigner's perspective. In this sense, Alice's memory is 'malleable' in that it is only determinate after Wigner's measurement. However, what is unclear is how he proposes to avoid solipsism if he wishes to allow for Alice and Wigner to have independent beliefs about what has (and hasn't) occurred in the lab. (That is, despite his goal, his approach seems to ensure consistency within each perspective, not across multiple perspectives.) Moreover, his focus on subjective experience seems to demand some sort of dualist metaphysics. Although he seems to want to maintain physicalism, he asks: "What if we replace both Wigner and his friend with some machinery? Would there ever be a collapse? Does it make sense, and is there any necessity to attribute consciousness to this unspecified machinery? Now that is pure philosophy and metaphysics. At any rate, *to get any objective readout and to discuss anything, we must involve a subjective experiencer at some point*." [26, p.11, emphasis added]. Of course, a view that posits such a dualism may be perfectly coherent, but I take it as preferable to present a theory that avoids it, if possible.

What then might the perspectivalist do to avoid 'brainwashing' Alice? Recall that perspectivalism holds unitary evolution to be universal. This implies that given some system S_1 observes a break in unitarity in the evolution of a system s, (i.e. observes a single outcome of a measurement on s), we can imagine another system S_2 for which the measurement is described as a unitarily entangling process – we've seen precisely this in Wigner's treatment of Alice's measurement. But by looking to this unitary treatment of *Wigner and Alice*, the perspectivalist can explain why it is that their results are necessarily correlated. That is, if we consider a unitary treatment of Wigner's 0/1 measurement by some 'super-superobserver', Xigner, we find that the state $|A+\rangle_A \, |Ready\rangle_W$, where A is Alice and W is Wigner, will evolve to the state $\sqrt{1/2}(|A0\rangle_A \, |W0\rangle_W + |A1\rangle_A \, |W1\rangle_W)$, where $|W0\rangle$ and $|W1\rangle$ are the states of Wigner having observed that Alice has observed 0 and 1, respectively. Importantly, this state doesn't contain terms that correspond to Alice having observed 0 while Wigner observes her having observed 1, or vice versa. This, says the perspectivalist, is all that is needed to physically ensure that their results are correlated. Taking quantum mechanics to be our fundamental physics, there is nothing further to explain. Asking for more is equivalent to asking why it is not the case that $F = 1/2ma$, for example.

Now appealing to the universality of unitarity may ensure consistency, but it raises two concerns. The first is that this again places pressure on the perspectivalist's claim that the Born rule probabilities can be understood as genuine. The second is that it becomes immediately clear that maintaining consistency between Wigner and Xigner will require considering a further system – a super-super-superobserver – and so on. Thus, we need to ensure that this explanation for inter-perspectival consistency doesn't demand a problematic infinite regress.

2.2.2.1 Born probabilities reconsidered

The clever perspectival skeptic has been waiting for an argument like this, and now steps in to point out that we've neglected an important point: Alice measures *first*. Knowing this Wigner could reason as follows:

1. Alice will make a measurement at time t_0. I will make my measurement at time t_1.
2. In her perspective Alice will observe a single outcome upon making her measurement.
3. My result will be perfectly correlated with what she observes, as dictated by the unitary treatment of my measurement.
4. Therefore, at time t_0 (prior to my measurement) I either have a 100% chance of observing $|A0\rangle$ or a 100% chance of observing $|A1\rangle$.
5. But the Born rule tells me that I have a 50% chance of observing $|A0\rangle$ and a 50% chance of observing $|A1\rangle$.
6. $\therefore$ Given that Alice's measurement results in a single outcome and that my result is perfectly correlated with hers, the Born rule probabilities to do not describe genuine possibilities.

At first, this reasoning appears to allow Wigner to come to contradictory conclusions about the probabilities of his measurement outcomes without positing determinate values of Alice's. Were this the case, this would indeed be problematic. However, 4. is an invalid step here, as it requires that Wigner 'raise' the determinateness of Alice's outcomes to his perspective. What Wigner can say is the following:

4*. Therefore, *in Alice's perspective* at time t_0 I either have a 100% chance of observing $|A0\rangle$ or a 100% chance of observing $|A1\rangle$.

That is, as a good perspectivalist, Wigner can know that other perspectives will have observed results that don't exist in his physics. In other words, Alice having measured before Wigner doesn't permit him to treat her as having obtained any determinate outcome.

2.2.2.2 Infinite worries

The second worry is that this response requires a problematic infinite regress to maintain inter-perspectival consistency. If consistency between two perspectives is maintained by considering a third, then to ensure consistency between the first two and the third will require a fourth, and so on. This was raised by an anonymous reviewer to [49], as well as in personal conversation with Matthew Leifer, but neither offered a detailed explanation of the worry. There seem to be at least two reasons this could be considered problematic:

1. The concern might simply be that the need for an infinite number of perspectives seems to weaken the explanatory power of the response. If we're considering Alice and Wigner, for example, we do not want to have to appeal to an infinite number of perspectives to maintain consistency between their measurement results.

If this is the worry then it seems mistaken. To maintain consistency between Alice and Wigner requires only a single perspective in which they both evolve unitarily and certainly doesn't require an infinite regress. Formalizing this will help demonstrate:

1. Alice has made a computational basis measurement and oberved $|0\rangle$.
2. Wigner will then measure her in the $\{|A0\rangle, |A1\rangle\}$ basis.
3. Xigner, our super-superobserver will describe the combine Wigner+Alice system evolving to the entangled state $\sqrt{1/2}(|A0\rangle|W0\rangle + |A1\rangle|W1\rangle)$ as above.
4. If Xigner makes a similar non-invasive measurement on the Alice+Wigner system in the basis $\{|A0\rangle|W0\rangle, |A1\rangle|W1\rangle\}$, then the possible contradictions between Wigner's and Xigner's perspectives are either (1) that Wigner observes $|A0\rangle$ while Xigner observes $|A1\rangle|W1\rangle$ or (2) that Wigner observes $|A1\rangle$ while Xigner observes $|A0\rangle|W0\rangle$. (Of course, these could be determined to be impossible by considering Yigner, who will treat Alice, Wigner and Xigner as all evolving unitarily, but this is not necessary here.)
5. Importantly, neither of these combinations of results introduces a possible inconsistency between Alice and Wigner. That is, even if Wigner and Xigner observe contradictory results, these results independently maintain perfect correlations between Alice and Wigner.

Thus, we don't need any perspectives beyond Xigner's to maintain consistency between Alice and Wigner and this possible concern is evaded.

2. The second possible concern is that this approach demands that the universe contain an infinite number of systems to ensure there are enough perspectives to maintain consistency universally.

It may be correct that maintaining consistency across *all* perspectives will require an infinite number of perspectives. However, even if this is so, it isn't obvious that this is troublesome. First, note that if a perspectival theory allows for all systems to act as observers, then all that would be needed to ensure the consistency between Alice and Wigner will be a single elementary particle from whose perspective they evolve unitarily. Looking then to whether this 'Xigner' particle's perspective will be consistent with what occurs in the perspective of a second 'Yigner' particle, it isn't obvious that this matters. Whether or not particles can act as observers, they are not the type of system that typically exhibit Boolean behavior, and so it may not be a problem if we lose consistency at this level as we've seen that it's already maintained between Alice and Wigner regardless. Pursuing this line of response, however, demands a significant amount of work and will only apply to theories that reject some minimal size or complexity requirement for being an observer. I want to suggest another response instead.

Recall that the perspectivalist takes unitary evolution to be the true fundamental dynamics of the universe. As such, when we talk about Xigner we are positing a hypothetical system whose perspective allows us to consider how Wigner and Alice become entangled. Xigner does not need to actually exist though, let alone measure the Wigner+Alice system, for the unitary treatment to be correct. Alice and Wigner evolve unitarily regardless of whether anyone is watching. As such, the perspectivalist may simply explain that we don't need to worry about maintaining consistency between hypothetical systems, in which case we don't need to worry about any further perspectives at all.

This response is further strengthened by considering similar cases from elsewhere in physics where the addition of hypothetical systems function to ensure that laws are maintained. For example, if we determine that a system's energy drops unexpectedly during some process, we assume that there must be some energy gained in the surrounding environment. Similarly, when we model thermodynamic systems we often need to include a heat bath if we want to ensure that the second law is upheld. But in order for these additional systems to successfully uphold these laws, they must themselves be treated as ideal. When we add a system to maintain the conservation of energy, for example, we must assume that this system is otherwise perfectly energetically isolated. (In other words, we must assume that the law in question is upheld!) If we were to treat this system realistically, we would find that we would need to include a further system to properly maintain conservation. Treating this third system carefully would require the addition of a fourth, and so on. In the case of maintaining inter-perspectival consistency, the perspectivalist is performing the same type of process here. We take unitary evolution to be universal and add hypothetical systems to see how this works. Just as we don't worry about maintaining energy conservation beyond the one hypothetical heat bath (or we idealize the heat bath, perhaps by giving it an infinite specific heat capacity), the perspectivalist need not worry about maintaining consistency beyond one hypothetical perspective.

Thus, regardless of how this worry is cashed out, we see that it's either based on a misunderstanding or makes unfair demands on our perspectival theory – demands that are not made in analogous cases in other physics.

2.2.3 Putting perspectives together

Having dealt with these worries, we've seen that the perspectivalist response to non-invasive encapsulated measurements involves two parts. First it maintains that the Born probabilities represent genuine possibilities insofar as they are the correct physical predictions of measurement outcomes. Second it appeals to the universality of unitarity to ensure consistency of measurement outcomes across multiple perspectives. There is a sense in which the perspectival physicist may stop here. She may explain that she has offered all that she needs to give an account of how non-invasive measurements are not problematic for her theory. However, in describing this I have frequently pushed aside metaphysical questions and concerns. I have also made some counter-intuitive claims about genuine probability and its relation to metaphysical possibility. As such, what I wish to discuss now are the philosophical commitments that come with such a physical theory.

There are likely multiple routes we might take to consider the philosophical implications of perspectivalism. However, one stands out due to its rather direct links to determinism and physics, not to mention our strong intuitions about it, and this to address the question of causation.

Looking to the case of Alice's and Wigner's measurement outcomes, it seems we are faced with a rather immediate intuitive conflict. On one hand, if Alice's outcome is non-existent in Wigner's physics, then it seems like we must deny that there is any physical causal arrow from Alice's outcome to Wigner's. That is, there can be no physical law that produces Wigner's outcome from Alice's result in Wigner's perspective. This may seem to be a difficult claim in itself, but we have learned from relativity theory that physics can have surprising consequences to our intuitions about causation. (Moreover, as Bell notes, and his theorem proves, quantum measurements are very different from classical ones in that their results do not (at least in general) "[refer] to some pre-existing property of the object in question." [19, p.34].) On the other hand, the fact that Wigner's outcome is perfectly correlated with Alice's, combined with the fact that we take Alice's result to temporally precede Wigner's measurement (from our 'extra-perspectival' point of view), seems to demand a causal explanation. That is, it seems that it must be the case that Alice's results causes Wigner's *in some sense*.

In the next chapter I will examine what the perspectivalist should say about this. I will argue that appealing to Humean supervenience theory will do the perspectivalist well. It will endorse a theory of causation that can support the claim that Alice's outcome causes Wigner's while holding the Born probabilities to be genuine, and even more, it will offer us a path to building a metaphysical theory that can inform other questions that have been raised – perhaps most notably about whether or not all systems can be treated as having a perspective.

Chapter 3: The Humean help

3.1 Why neo-Humeanism

What I wish to develop here is a direction for the perspectivalist that leverages the well-established theory of Humean supervenience. The goal is an account that maintains the 'genuine' status of the Born probabilities without denying our intuition that Alice's result in some way causes Wigner's. That said, my claim here is not that the perspectivalist *must* adopt a neo-Humean or Lewisian causal theory or metaphysics. Rather, I want to demonstrate that Lewis offers a plausible theory of causation for perspectivalism, and as such, provides a direction for us to take in developing a full metaphysical theory.

I will first look at what the perspectivalist requires from a causal theory and use this to motivate looking to a counterfactual theory of causation. To do this I will explain why other standard approaches to causation seem to be poor choices, and then argue that the neo-Humean regularity/counterfactual causal theory looks to meet the perspectivalist demands. Having done this, I will turn to the metaphysics that can ground such a causal theory in order to determine what types of ontological and nomological models are available to the perspectivalist. This involves defining a *mosaic* of events in spacetime and a *best system* of laws that supervenes on it. Finally I will conclude with a toy model to demonstrate how the approach can meet the needs of the perspectivalist framework.

3.1.1 Finding a cause

The perspectivalist has a few immediate demands from a causal theory: First, the theory must be one that does not predetermine Wigner's outcome within his perspective. In other words, it must allow room for indeterminism in Wigner's perspective given the Born rule. Note that this is not the standard demand for indeterminism that one finds in discussions of causal theory. Typically (and especially in the context of causal modeling in quantum mechanics) we wish a causal theory to be robust under the introduction of indeterministic laws or in an indeterministic world. (See, for example, [50], [6], [51] (and references therein), [52, Chps.14 & 17], and [53, §4.3].) This demands a theory to allow for A to be a cause of B even when there is a chance for A to occur without B to follow. A standard example would be that smoking causes cancer, even though it is possible to smoke without developing the disease. In our case we are not suggesting that if Alice observes $|0\rangle$ then there is merely some probability of Wigner observing $|A0\rangle$. Their results are perfectly correlated. Rather, what we need is a theory that allows for it to be the case that Wigner's result is not determined by any physical laws (in his perspective) while also being caused (and perfectly correlated) with Alice's.

Second, we would like a causal theory that can provide perspective-independent descriptions of causal structures. We do not want it to be the case that A causes B in one perspective but not in another. This is clearly intuitively desirable – it would seem strange to conclude that Alice's result causes Wigner's result in her perspective but not in his. After all, according to perspectivalism, Wigner can know that his result will be perfectly correlated with Alice's and may, therefore, describe his result as caused by hers even though he maintains that his result is undetermined prior to his measurement. (This mirrors the fact that the perspectivalist has suggested that genuinely possibility may not be subsumed by metaphysical possibility.) What this implies, though, is that our causal theory must be able to consider variables that do not physically co-exist. That is, we need a causal theory that can talk *as if* Alice's outcome is determinate in Wigner's perspective despite the fact that it isn't.

Putting these two requirements together, we can make a few generalizations. For example, we cannot have a theory that depends purely on physics to determine causal relations. As Alice's outcome doesn't exist in Wigner's physics there is no way that Wigner would be able to identify a physical law that would permit him to say that her result caused his. As Alice would say otherwise, a physics-based theory would necessarily be perspective-dependent. This immediately rules out any sort of deductive-nomological model,[1] as well as theories that explicitly depend on physical interactions between Alice and Wigner. Salmon's early process theory [52, 55], for example, requires an interaction between Alice's

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[1] See [52, chp.7] for a discussion of the deductive nomological theory. I will not go into this theory here, though. As Weatherson say, "[t]here are so few supporters of deductive-nomological theories in contemporary metaphysics that a modern paper would not spend nearly so much time on them[!]" [54, §5.2].

and Wigner's "causal processes", or world lines[2] (or perhaps more precisely, one of the causal processes of the subsystems of Alice's lab and one of the causal processes in Wigner's measurement device).

The difficulty here is that the case seems to put pressure on a circularity in Salmon's theory first noted by Dowe [56]. Central to Salmon's early theory is that a causal process[3] must be able to transmit a "mark," or some sort of information: "It has always been clear that a process is causal if it is capable of transmitting a mark.. . . The fact that it has the capacity to transmit a mark is merely a symptom of the fact that it is actually transmitting something else. That other something I described as information, structure, and causal influence." [52, p.258]. However, as Dowe explains, Salmon's definition of a "mark" relies on the definition of a causal interaction, introducing circularity into the theory. [56, §3.1]. This is exemplified in our case by considering Alice's causal process in Wigner's frame. The difficulty here is answering the question of whether Alice's causal process can contain a mark, or information, about her outcome. If we appeal to the fact that her outcome doesn't exist in Wigner's physics, then it seems like Alice's process cannot carry a mark, and so the interaction of their processes should not be considered a causal one (at least with respect to the possible causal relationship between their outcomes). On the other hand, if we consider that it does carry this mark, then we can ask what justifies this claim. And the only answer available

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[2] I do not wish to enter into a discussion of what does and doesn't count as a causal process for Salmon. For our purposes I follow Dowe [55] in describing it as a world line. See [52, chps. 1, 7,12, and 18]

[3] Causal processes are distinguished from pseudo-processes, which are unable to carry a mark. See [52, Chp.7 §3].

(given that her outcome doesn't exist for Wigner) is the fact that we wish to describe their processes' interaction as causal.

Dowe's response to the circularity is to develop his 'conserved quantity' revision of Salmon's theory [56] (later adopted by Salmon as well. [52, chp. 16]). However, this will prove equally unsatisfactory for the perspectivalist. Dowe (and later Salmon) defines causal interaction as "an intersection of world lines which involves exchange of a conserved quantity." [56, p.210]. Looking to the case of Alice and Wigner, there is no immediately obvious quantity that we might point to as being conserved when discussing their measurement outcomes. Consider, for example, the simple case of one billiard ball striking another. Here our physics explains that the transference of energy/momentum indicates a causal interaction, and this is necessarily reflected in the change to the energy/momentum of the states of each system after the interaction. In the case of Alice and Wigner, though, their interaction involves no necessary change to Alice's state at all from her perspective. (And to posit a change to her state from Wigner's perspective will be somewhat tricky, as was discussed in §2.2.2.)

As we've seen, a more careful analysis of the measurement will necessarily involve some interactions at the microscopic level between Wigner's measuring device and at least some particle from Alice's lab. The theory may then explain that this is the causal interaction that we should be concerned with when looking at Wigner's measurement. The problem here is even simpler than in the case of Salmon's process theory. If causal interactions are determined by the exchange of a conserved quantity, then things become tricky in the case of quantum interactions as quantities are generally not conserved through breaks in unitary evolution[57]. This may seem like a superficial problem – the definition of causal interaction may not demand that the conserved quantity actually *be* conserved in the interaction. Thus, we might imagine that we can identify conserved quantities from our classical conservation laws, and then look to quantum interactions and ask whether these quantities are exchanged regardless of whether they are conserved. However, some reflection will quickly find this approach troubling. If the quantities are not, in general, conserved in a quantum measurement, then it is not clear how to avoid circularity in defining an 'exchange' of these properties. For example, say a system's momentum has been measured to be p_1. It evolves in time before colliding with another system that is at rest (relative to some observer) at some position x. If we treat this collision as localizing the particles' positions, then after the collision the particles will be in an entangled superposition of momentum states that permits a momentum measurement on the second particle to obtain some result $p_2 > p_1$. Because the momentum observed surpasses the momentum initially 'available' in the collision, it doesn't seem obvious that there has been an 'exchange' here at all. We might, of course, posit that this result somehow represents evidence that a momentum exchange has occurred, but I don't know what motivation could be provided for this that doesn't somehow assume the state of the second particle to have been *caused* by the state of the first. Of course, conservation laws do hold in unitary quantum dynamics and I am not claiming here that a theorist could not develop a fully consistent account of causation in terms of conserved quantities should she have good reason to do so. Rather, I hope it's clear that this approach comes with such high hurdles for the perspectivalist that it seems unnecessarily difficult.

Looking to other theories then, one tempting option might be to look to manipulation or intervention-based theories. However, they are also immediately ruled out by the fact that Alice's result does not exist for Wigner.[4] The view is nicely stated by Woodward: "on a manipulability account of causation, it is most perspicuous to think of causal relationships as relating variables or, to speak more precisely, as describing how changes in the value of one or more variables will change the value of other variables." [59, p.39]. He later summarizes the "point of departure" of these theories as follows: "causal relationships are relationships that are potentially exploitable for purposes of manipulation and control. Very roughly, if C causes E then if C were to be manipulated in the right way, there would be an associated change in E. Conversely, if there would be a change in E, were the right sort of manipulation of C to occur, then C causes E." [58, 234]. The difficulty with these theories is likely apparent from these descriptions. To base a causal relationship from A to B on results of manipulating the value of A presupposes the ability to consider A as having a determinate value that can be manipulated. That is, we cannot question the result of manipulating A if A is indeterminate or doesn't exist, as is the case in the situation we're concerned with.

There is a further option available should someone wish to pursue this line. The reason we assumed that Wigner could not treat Alice as having ob-

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[4] See [58] for a survey of these theories.

served a single outcome is that this would result in incorrect predictions for other measurements that Wigner could make. However, if Wigner were to hold his measurement fixed then this could limit his consideration to cases wherein he might treat Alice's result as determinate. (Note that this is only obviously going to be alright for non-invasive measurements whose possible outcomes each correspond to one of Alice's possible outcomes, as in the 0/1 measurement.) In this case he might be able to imagine manipulating her result to determine the causal relationship. Indeed, the interventionist causal scheme typically includes holding other relevant variables fixed. (See [58, p.250-252].) However, I would argue that this suggestion violates what Wood and Spekkens call *Faithfulness* or the *no fine tuning* principle:

> **Faithfulness** (no fine-tuning): The probability distribution induced by a causal model M (over the variables in M or some subset thereof) is faithful (not fine-tuned) if its [conditional independencies] continue to hold for any variation of the causal-statistical parameters in M.
>
> In other words, all [conditional independencies] should be a consequence of the causal structure alone, not a result of the causal–statistical parameters taking some particular set of values. If one assumes a uniform prior over the space of causal–statistical parameters, then the parameter choices that can explain [conditional independence] relations that are not implied by the causal structure are found to have measure zero. [60, p.9].

Admittedly, holding Wigner's measurement fixed does not seem like a standard case of fine-tuning. Typical examples involve some variables, A and B with possible causal influence on a third variable C, such that manipulations on the value of B cause no effect on C *for a particular value of* A. In this case it would be incorrect to assume conditional independence of C on B.

In the case presented, we are imagining two relevant variables, Alice's result A and Wigner's measurement choice M, both as possible causal influences on a Wigner's result W.[5] What is different here, of course, is that we are not discovering an apparent conditional independence between two of these variables by setting the value of the third. (That is, we are not manipulating M and discovering an artificial causal independence of W on A, for instance.) Rather, what we have is an artificial conditional *dependence* that appears between A and W because the variable A only appears relevant for a particular value of M. More to the point, as soon as we consider different values for M we know that A is replaced by a parameter (or set of parameters) ψ that represent the quantum state Wigner uses to describe Alice. What this reflects is that a causal network composed only of A, M and W is fine-tuned in that it makes W appear to be independent of ψ. Once this is recognized we find that we cannot build a model composed of A, W, M and ψ that includes both probabilities determined by the Born rule and a causal connection between A and W.

Again, there may be a way around this problem, but once again I argue

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[5] If one is concerned, note that is standard to distinguish variables for measurement choice and measurement outcome. This is reflected, for example, in standard treatments of Bell's theorem, (including the no-signaling principle and outcome independence). See [61] for a recent example of quantum causal modeling that makes this explicit.

that without some independent reason to pursue the interventionist approach, it seems that this causal theory seems inappropriate.

3.2 Counterfactual causation

There may be other or more nuanced theories of causation that one might want to consider before looking to neo-Humean causation. However, I do not know of one that will not be dealt with in the same manner as one of those above (or that will lead us to a different conclusion than that which I suggest here). As such, I will proceed with an argument for why the counterfactual path seems to be a fruitful one. I will begin with a brief review of Lewis's counterfactual theory of causation (including some context of its development) and will then explain how this fits well with the perspectivalist position.

Lewis first presents his theory of causation in his [62]. He begins with a quote from Hume: "We may define a cause to be an object followed by another, and where all the objects, similar to the first, are followed by objects similar to the second. Or, in other words, where, if the first object had not been, the second never had existed." [63, §VII]. It is routinely noted[6] that this quote seems to imply a confusion. While the first sentence indicates a regularity theory of causation, this second sentence seems to equivocate this with a counterfactual definition. As Lewis says, and Menzies explains [64], neither Hume nor those who followed him pursued the counterfactual definition that he suggests, at least partially because there was not a standard semantics of counterfactuals until the 1970's.

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[6] See, for example, [62] and [64].

The counterfactual theory that Lewis provides here may be seen as an evolution (as compared to a rejection) of the regularity-based theories of causation that preceded him. As this evolution will directly impact what follows in sections 3.4 and 3.5, it is worth giving a brief (and rather simplified) account of the progression from Humean to neo-Humean causation:

Psillos's [65] describes the "kernel" of the "regularity view of causation" (RVC) as follows:

> *c* causes *e* iff
>
> 1. *c* is spatiotemporally contiguous to *e*;
> 2. *e* succeeds *c* in time; and
> 3. all events of type *C* (i.e. events that are like *c*) are regularly followed by (or are constantly conjoined with) events of type *E* (i.e. events like *e*).
>
> . . . Causation, that is, is built up from non-causal facts, more specifically two particular facts and one general. A corollary of RVC is that there is no extra element in causation which is of a fully distinct kind, like a necessary connection or a productive relation or what have you—something, moreover, that would explain or ground or underpin the regular association. [65, p.131-132].

What is immediately attractive to the perspectivalist here is the rejection of any necessary grounding of causal relations - any "necessary connexion", as Hume says. By reducing causation to regularity, Alice's outcome can be seen as a cause of Wigner's independently of any dynamical description of how we get from one to the next. However, this naïve regularity theory is immediately problematic in that it is unable to distinguish between direct causation and multiple effects of a common cause. As a simple example, say events of type X are always followed by events of type Y and Z such that the Y-type events precedes the Z-type events and the two occur spatially close to one another. There are two immediate causal models available: a direct causal model in which X causes Y and Y causes Z, and a common cause model in which X causes both Y and Z independently of one another. The difficult, of course, is that appealing to mere regularity doesn't permit any way to differentiate these models from one another. The answer to this is to differentiate a set of regularities that indicate causal relationships – those deemed *laws of nature* – and those that don't.

Paul and Hall explain that such an appeal to laws gives rise to two forms of regularity accounts. [53, p.14-16]. The first, which they associate mainly with Davidson, claims that C causes E when they can be described in a manner that is 'covered' by a law. That is, if there is some law that describes the universal regularity of α type states of affairs evolving to β type states of affairs, and C and E can be described as α and β type states of affairs, respectively, then C causes E. The second, which they ascribe to Mackie (and describe Lewis as responding to), appeals to a sort of nomic sufficiency. They offer the following definition for this:

> C causes E iff C and E both occur, and there is some suitably chosen auxiliary proposition F describing the circumstances of C's occurrence

> such that (i) in any nomologically possible world in which C occurs and F is true, E occurs; (ii) in some nomologically possible world in which F is true, and C does not occur, E does not occur. In short, C is an essential part of some set of ontological conditions that are lawfully sufficient for E. [53, p.14].

Of the two forms, Paul and Hall reject the first as inadequate due to the fact that any definition of "law" it might offer seems problematic. It is not necessary to recount the details of their argument here[7] but note that this form does not provide a means of correctly distinguishing between the direct and common causes. If the world is such that Y and Z always follow X events in the example above, and Y events only ever follow X events, then it will be universally true that X events are followed by Y and Z events and that Y events are followed by Z events, and so presumably laws can be defined that describes each of these.

Looking to the second form we find an indication that appealing to counterfactuals will help differentiate causes from other regularities. The definition here assumes a differentiation between what Lewis calls "law propositions," which determine the nomologically possible, and "propositions of particular fact," which Paul and Hall subsume under F in the definition above. Thus, we begin with some set of nomological constraints (which remains to be properly described) and then we consider whether what is contingently true (F) ensures that E follows C. Now the problem of distinguishing direct from common cause still remains – F is too generally described to be able to isolate causes. As such, Paul and Hall suggest

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[7] See [53, p.38-44].

the following constraint: "the set S of causes of an event E should collectively suffice for that event, but should do so nonredundantly: i.e., no proper subset of S should suffice for E. Then S had better not include all the causes of E, occurring at any time, since later ones will render earlier ones redundant, and vice versa."[53, p.14].[8] This allows us to say, for example, that Y cannot be a cause for Z because it is insufficient, according to what is nomologically possible, to ensure Z. Rather, we need to go back to X to ensure sufficiency.

This may seem to be tangential to Paul and Hall's focus on redundancy, but this is where (as they describe) counterfactual reasoning comes into play. To see how this works, consider the following causal model: There are two events, X and Y, which are spatiotemporally near one another. Event Y causes a third event Z. We need a definition that avoids describing X as a cause of Z. Taking the set of 'propositions of particular fact' prior to Z will include descriptions of both X and Y. However, if we want to make this set of propositions non-redundant (again, given some set of nomological possibilities) we must drop the description of X. This will achieve what is desired but to arrive at this conclusion we must counterfactually reason about what would happen if X had not occurred.

This is not quite how Lewis arrives at his counterfactual definition of causation, though it is not far off. Lewis notes that regularity theories fail to deal with certain types of cases, including those like the one just described, and suggests instead the counterfactual definition of cause: C causes E if C is counterfactually dependent on E – if it is true that had C not occurred, E would not have occurred.

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[8] This suggestion is similar to one Psillos presents in [65].

What is then required to determine causation, of course, is a means of evaluating the truth of counterfactuals. Moreover, insofar as counterfactuals must have non-trivial truth valuations, we need to find some sort of constraint that determines, for instance, which of "Had P then Q" or "Had P then $\neg Q$" is true. These are both provided by Lewis's full theory of Humean supervenience, which I will turn to now. After giving a brief outline of the standard approach I will discuss how it can be adapted for by the perspectivalist to give a comprehensive and clear account of both the causal and physical claims that we have comes to above.

3.3 Humean supervenience

Lewis describes the foundation of Humean supervenience in the introduction to his [5]:

> Humean supervenience is named in honor of the greater denier of necessary connections. It is the doctrine that all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another. . . . We have geometry: a system of external relations of spatiotemporal distance between points. Maybe points of spacetime itself, maybe point-sized bits of matter or aether or fields, maybe both. 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. There is no difference without difference in the arrangement

> of qualities. All else supervenes on that. [5, p.ix-x]

Lewis's ontological picture is rather simple: there are nothing but properties at spacetime points or local regions. From this mosaic, Lewis proceeds to give his *best system account* of laws:[9] Given the entirety of this mosaic, laws are those propositions that together form an axiomatic deductive system that best balances strength and simplicity. [50, p.478-479][10]

The intuition here seems straightforward enough. If we wish to describe the universe as composed of nothing more than local matters of fact then there is nothing to appeal to when we ask what makes laws like $F = ma$ true – the law has no special power, nor does it represent a further 'connexion' between the local properties or matters of fact that compose the mosaic. As Hume wrote,

> there appears not, throughout all nature, any one instance of connexion which is conceivable by us. All events seem entirely loose and separate. One event follows another; but we never can observe any tie between them. They seem conjoined, but never connected. And as we can have no idea of any thing which never appeared to our outward sense or inward sentiment, the necessary conclusion seems to be that we have no idea of connexion or power at all, and that these

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[9] This approach follows Mill and Ramsey, and is often called the Mill-Ramsey-Lewis theory of laws, but I do not wish to look at the full historical development here. For a brief discussion see [66].

[10] I will not offer a fully detailed discussion of the literature on the best system account here as this is outside the scope of my project. Note that I will not fully defend the approach either, as I am not claiming that it is the only metaphysics available to the perspectivalist. Recall, my position is that a counterfactual theory of causation suits the perspectivalist, and that Humean supervenience offers a path to describing a metaphysical foundation that can be used to ground such a causal theory. See Bialek's doctoral dissertation [67] for a more comprehensive, yet succinct discussion of the best system account and its history.

> words are absolutely, without any meaning, when employed either in philosophical reasonings or common life. [63]

Thus, the laws reflect patterns in the arrangement of properties. What makes $F = ma$ true are the instances in which it is it true (and the absence of cases that invalidate it) and what makes it a law is that it is included in the best systematization of the events in the mosaic.

Together, the mosaic and the best system of laws allows Lewis is able to ground his semantics of counterfactuals. If some event P actually occurs, then we evaluate the counterfactual, "had P not occurred, Q would have occurred", or $\neg P \mathrel{\Box\!\!\rightarrow} Q$ in Lewis's notation, as follows: We start with the (set of) possible world(s) where everything up until the time that P occurred is exactly as it actually is. We then imagine a "tiny miracle takes place," as Lewis says in [68] which amounts to a violation of the actual laws of nature that prevents P from occurring. From here we see how this world evolves (or worlds evolve) under the laws, evaluating the counterfactual as true if Q occurs.[11]

It is worth quickly putting aside a common worry about quantum mechanics in Lewis's metaphysics as the two have historically been seen as generally incompatible without significant 'tweaks'. As cited above, Lewis explains that "all there is to the world is a vast mosaic of *local* matters of particular fact" (emphasis added). But as Lewis also notes, quantum mechanics seems to make this difficult: "maybe the lesson of Bell's theorem is exactly that there are physical

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[11] This is a very brief and superficial description of the semantics, of course. For more details see [68].

entities which are unlocalized, and which might therefore make a difference between worlds. . . that match perfectly in their arrangements of local qualities." [5, p.xi].[12]

Loewer is likely the first to address this problem. In [6] he argues that the Bohmian may avoid conflict with Humeanism by 'moving' into fundamental $3n$-dimensional configuration space (for n particles in the universe). Here lives the Bohmian 'world particle' and the quantum state, which assigns local values to points *in that space*. The world we observe then supervenes on these values: "If Bohm's theory is the correct and complete physical theory, and if physicalism is true, then everything would supervene on the quantum state and the location of the world particle. We can think of the manifest world – the world of macroscopic objects and their motions – as shadows cast by the quantum state and the world particle as they evolve in configuration."[6, p.104].

My point here is not to critically analyze Loewer's response. Rather, what I wish to point out it that Lewis's and Loewer's concerns do not affect the perspectivalist. The conflict arises only by taking the quantum state to represent an ontological state. By taking quantum mechanics to be probabilistic, we are not forced to understand entangled states as representing non-local properties the mosaic. Rather they can be understood as merely providing a description of probabilistic matters of fact conditional on measurements of each of the entangled particles. Of course, we also find that there are non-local correlations in these predictions, but these can be understood as correlations between local matters of

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[12] See also [50, p.474].

fact – nothing non-local needs to enter the ontology.

Although I don't wish to argue that the perspectivalist is necessarily committed to this metaphysics, one benefit of appealing to counterfactual theories of causation (and Humean supervenience) is that we are given a 'recipe' to proceed: we must describe a mosaic and from it, a best system account of the laws of physics. One hiccup in this direction, however, is that we haven't much to start with to build our mosaic. In term of ontology, all that we've done so far is (1) to reject representationalism and (2) to claim that Alice's and Wigner's outcomes 'exist' in their perspectives. Respectively, these imply (1) that we do not wish to posit a mosaic made of quantum states (i.e. quantum properties) at spacetime regions (be they localized or not), and (2) that Alice's and Wigner's outcomes should be represented in the mosaic if we wish to avoid solipsism.

On the other hand, our considerations so far will have a significant impact on what we might say about the best system account of laws that we must adopt. We've assumed quantum mechanics to be correct and complete, which implies that it should hold a central position in our best system. We've also assumed that quantum predictions are perspective-dependent. Putting these together though, this means that the best system may result in different predictions from different perspectives, which is a claim that must be carefully considered. Thus, I propose that we work backwards - I will begin by discussing what the best system must look like and then use this to consider the possible ontologies that remain on the table.

3.4 The best system

For Lewis there is an objective truth about the best system of laws – a correct system that objectively balances strength and simplicity and that supervenes on the entirety of the mosaic. Although a number of concerns are raised against this view, I will not give a full survey of the best systems account literature as this would take far too much time and much of it is unrelated to what I present here. (See footnote 10.) Rather, I wish to focus on a few concerns that will resonate with what we have said so far about the perspectival approach. Perhaps not surprisingly, these have to do with (1) epistemic access to the mosaic and (2) Lewis's "big bad bug" – indeterminism and chance in the best system account. I will explain the concerns briefly, and then show how they relate to the perspectivalist. This will point to an interesting suggestion for the of the best system account, which is the adoption of indexicalized laws.[13] – a system that is explicitly meant to be used from *within* the mosaic (despite its being possibly informed by, and supervening on, the entire mosaic)

3.4.1 Epistemic and probablisitic concerns

Even under the umbrella of "epistemic access to the mosaic" there are a number of concerns that I will not spend time on here. For example, one might worry that we live in a small part of the universe where the patterns in the

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[13] I would call this a "perspectival" best system, but this term has already been adopted by Halpin's approach, as will be discussed below.

mosaic provide evidence for a theory that is correct within our Hubble sphere (or indeed even a region much smaller), but not elsewhere. Such concerns parallel standard skeptical arguments (in both metaphysics/epistemology and philosophy of science), and there is a sense in which the theorist must acknowledge that this is always a possibility. Putting these aside, I will be concerned with more 'localized' worries that will lead to more fruitful considerations.

The first is attributed to Armstrong, though has been discussed by many.[14] Armstrong claims that a best system which relies on "standards" of simplicity and strength is bound to involve some level of subjectivity. As he says, "even granted that [these standards] are shared by all mankind, [they] may not be shared by other rational creatures. . . . Lewis also refers to 'our way of balancing' simplicity and strength. May there not be irresoluable conflicts about the exact point of balance?. . . If such a conflict arose, there could for Lewis be no truth of the matter." [70, p.67].

The concern is an intuitive one given any reflection on Lewis's claims. There may be a (relatively) clear notion of what kind of standard "strength" is. It certainly should involve, at the least, precision and accuracy. However, "simplicity" is hard to consider without some appeal to subjective variables (for example, language, context, subject matter, etc.)[15], and how these are balanced seem almost meaningless without conceiving of a rational agent to weight the relevant factors. Indeed, this worry is noted by Lewis himself in his later work on the theory:

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[14] See [67], [69, §1.2.1].

[15] See Bialek [67] for a discussion of such variables.

"The worst problem about the best-system analysis is that when we ask where the standards of simplicity and strength and balance come from, the answer may seem to be that they come from us." [50, p.479].

Lewis's response to the concern is somewhat dismissive. He explains that "[i]f nature is kind, the best system will be *robustly* best – so far ahead of its rivals that it will come out first under any standards of simplicity and strength and balance." [50, p.479]. He admits that we have no guarantee of nature's kindness, but notes that we have no reason to believe otherwise, and so suggests putting the worry aside until we gather evidence that the concern is real. Thus, in a sense, Lewis likens this concern to the wider skeptical one I've dismissed above and responds to it as one would typically respond to scientific skepticism.

This said, there is a closely related concern that Lewis may not be able to dismiss with such ease. Consider the following thought experiment (to use the term loosely!).[16] Assume, as the perspectivalist does, that we live in a world where our best system includes probabilistic laws. We meet some god (who has epistemic access to the entirety of the mosaic) and ask for a theory that describes the entirety of the universe. The god responds by starting to recount a list: "At time t_0, particle 1 has properties $\{p_1\}$, particle 2 has properties $\{p_2\}$, particle 3 has properties $\{p_3\}\ldots$ At time t_1 particle 1 has properties $\{p'_1\}\ldots$ At $t_2\ldots$" Given that the god's list essentially provides a complete description the properties that compose the mosaic, we certainly could use the list to form a maximally strong theory. However, note that this theory fails to be of any use to us in describing the

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[16] This has been given by Bialek [67] as well as by Loewer [71], albeit for different reasons.

evolution of the universe *systematically*. That is, it may do well to allow us to buy a winning lottery ticket, but if nature has, in fact, been kind to us before obtaining the list, this information would not help us further develop a best system. In fact, there are two reasons for this. First, given that nature has been kind to us, the list will not provide us with any new evidence upon which we might base (significant) changes to our current system. It would offer no more that verification of the predictions our system already makes. Second, a list of all the properties of all the particles in the universe may offer no help at all to develop a system beyond particle physics. That is, given such a description, it isn't obvious that we would be able to identify larger structures, from pebbles to planets or beyond, which typically play roles in our physical explanations.

The question, you might ask, is why we would need to form any kind of systematic description of the universe provided access to such a list. But this is precisely the point! As Stairs describes, "If we knew the mosaic whole and could juggle the details with godlike ease, we would have no use for probability– objective or subjective." [72, p.159]. The goal of the best system is to create a set of laws with which we might describe the mosaic *in the absence* of the 'god's eye view' of the mosaic. Thus, there is indeed a certain subjectivity that is *necessary* in a best system account that produces probabilistic predictions, but not one of the type that Armstrong has in mind. Rather, it comes from the fact that we are *part* of the mosaic.

One might think that my reasoning is backwards here as I've assumed the best system to be probabilistic from the start. If we start by assuming the laws of nature to be deterministic, then combining the best system with the state of the entire universe at some point in time *amounts* to the list provided by the god. In this case then there is less of a discrepancy between using the list and using the best system. However, while the argument may hold for a Newtonian universe, it fails in our universe even before we consider quantum indeterminism. Einstein has shown us that there are limitations to our access of other regions of the universe (i.e. the mosaic) – we cannot describe the state of the entire universe at a point in time.[17] As such, even in a deterministic universe there is a real difference between our using the best system to make predictions and the god's using it. In fact, we can generalize Stairs' claim to say "If we knew the mosaic whole and could juggle the details with godlike ease, we would have no use for any method of systematizing the universe to make predictions at all."

Acknowledging that the best system account only makes sense from within the mosaic, we find that dealing with the big bad bug may become even easier than Lewis had anticipated. As Lewis notes [50], there seem to be two ways that we might explain indeterminism in a best system of laws: it may reflect symmetries or it may be grounded in frequencies. He quickly dismisses symmetries as a possible source, as we can easily imagine chance events that do not have equiprobable outcomes but that do seem to exhibit perfectly symmetric conditions for each outcome. (This is especially true in quantum mechanics and comes up frequently, for example, in the context of describing probability in Everettian mechanics.)

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[17] Although it is true that there may be Cauchy surfaces in our past lightcones, I take it as granted that we don't have the ability to access the complete information found on these surfaces. (Thanks are due to Neil Dewar for raising this point.)

Looking then to a frequentist explanation, Lewis raises two standard types of problems here. First is the concern that for frequencies to ground our probabilities seems to demand that actual frequencies exactly match the theoretical probabilities. Thus, if the probability of an $|x+\rangle$ result when measuring x-spin on a $|z+\rangle$ qubit is truly 50%, then it must be that exactly half of all actual x-spin measurements on $|z+\rangle$ qubits in the mosaic result in $|x+\rangle$ (and half in $|z-\rangle$). This seems completely untenable, of course, and in fact the situation is even worse if we assign real number probabilities to events which can only occur a countable number of times. Lewis's response here seems correct. He notes that to demand this of the theoretical frequencies is to neglect that a best system is partially determined by the standard of simplicity. Imagine, for example, that across the whole of the mosaic the true distribution of $|x+\rangle$ and $|x-\rangle$ results when measuring a $|z+\rangle$ qubit is $(0.5+\epsilon)/(0.5-\epsilon)$ for $\epsilon \ll 0.01$. Then "[t]he system that assigns uniform chances of 50% exactly gains in simplicity at not too much cost in fit. The decisive front-runner might therefore be a system that rounds off the actual frequency." [50, p.481].

It's worth noting that underlying Lewis's position is again an assumption that the best system is only a useful systematization from within the mosaic. Given the god's list of all events in the mosaic, there would be no need to sacrifice strength over simplicity. Imagine that from this list we extract all events E which correspond to x-spin measurements of $|z+\rangle$ qubits, and from this extraction we calculate the exact frequency of the outcomes. If we then wished to blind ourselves to this list and make probabilistic predictions, we would know that we could 'do better' than our best system by using the actual frequency determined by the list rather than the best system.[18] In other words, given access to the god's list, there is not much to be gained by sacrificing strength for simplicity. If we knew that our systematization made any such sacrifices, then we would surely look to the list rather than the system to make any actual prediction.

The second type of problem Lewis is concerned with will again demonstrate the point. This is the question of what to make of probabilistic predictions of one-off events. Lewis gives the examples of an isotope that is very rare – so rare that only one ever such atom exists in the universe. Given that there are not enough instances of this isotope in the mosaic to establish a pattern, Lewis asks what it would mean to assign any probability ($\neq 0$ or 1) to the isotope decaying. Again, his response seems correct. And again, it demonstrates that the best system can only be 'best' from within the mosaic. Lewis explains that given such an isotope, we should assign probabilities to its decay based on the existing theory we have. "[These] atoms have their chances of decay not in virtue of decay frequencies,. . . but rather in virtue of these general laws." [50, p.478]. It is likely obvious how this demonstrates my general point here. Given the god's list there would simply be no point in assigning probabilities to the atom's decay at all beyond 0 or 1.

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[18] By 'do better' I mean our predictions would be more accurate. This may not be apparent in predicting a single event, but becomes rather obvious if we imagine predicting large numbers of events.

3.4.2 An indexical best system

It may now be obvious why I have highlighted this feature of the best system account. The result is neither surprising nor generally problematic for neo-Humeanism, but it mirrors the claim that our fundamental physics is only applicable from an observer's perspective and will help us further detail a perspectivalist position.

This feature of best systems hasn't been highly explored in the literature thus far. There are a few discussions that come close though. For example, Halpin [73] aims to contextualize laws of nature without giving up their objectivity. His "perspectival" best system account takes the language of theory and standards of scientific practice and methodology to be important factors in weighing theories against each other. [73, p.151].[19] Although it is not explicitly stated, it is clear that Halpin intends for this to be a theory that determines best systems from within the mosaic.

Ward [74] goes slightly further (and comes closer to my claims here). His "projectivist" account argues that the Humean laws should be understood as normative rather than descriptive in that "law claims. . . express attitudes regarding the suitability of rules for the purposes of prediction and explanation." [74, p.197]. Now for a law to be understood as normative, it must be normative for an agent. Thus, again, the best systematization is necessarily understood as 'best' from within the mosaic. But, moreover, in Ward's theory we have an explicit

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[19] The same is argued by Bialek [67].

description of the systematization as understood as developing predictions.

This does seem similar to some of what I have said here. As I've discussed above, the perspectivalist maintains that quantum mechanical probabilities are the correct probabilities to be used in predicting the outcome of interactions. However, I don't take Ward's position as a starting point for two reasons. The first is simply that he doesn't focus here on the possibility that a best system might result in differing predictions for different agents. Of course, this is precisely the case for the perspectival quantum theorist. Looking to encapsulated measurements, for example, different observers may make differing predictions about what will occur. The second is somewhat more severe, and this is that the quantum perspectivalist may wish to avoid claiming that the best system is fundamentally normative. Although such a move is meant to ease the metaphysical demands of the best system account for Ward, in the context of quantum theory this is not obviously the case as it requires an otherwise unwarranted distinction between observer and quantum system.

To see why this is the case, recall that we have taken quantum mechanics to be a probabilistic theory. If we take law claims to be normative in Ward's sense, then given (1) that quantum mechanics can only be applied from a perspective at a time and (2) that normative claims must be normative for an agent, it follows that only those systems which can be agents can be said to have perspectives from which the theory applies. Now even if the theorist claims that some level of complexity or size is required to count as an observer (i.e. to have a perspective), there are certainly systems that pass this threshold but that cannot count as an agent. (A supercomputer, or even a large rock, for example, are certainly large and complex enough to be treated as having perspectives, but they are not the type of things to which normative claims apply!) Thus, if the perspectivalist wishes to maintain that quantum probabilities are objectively correct, independently of whether or not an 'observer' is involved, she must take any normative claims that arise from the theory to be consequences of, not integral to, quantum mechanics.[20]

Thus, while both Halpin and Ward point in the right direction, neither offers a best system account that is entirely appropriate for the perspectival theorist. To build her best system, she needs to leverage the fact that the system must be used within the mosaic to match the central claims of her position. The direction I wish to suggest for the perspectivalist, therefore, is the following: Assuming that quantum mechanics is indeed (at least part of) the best system, allow for this system to include some *indexicalized* content. Thus, the best system says that, given a point or region in the mosaic, all systems outside of this region will appear to evolve unitarily and that the results of interactions with these systems will be described by the Born probabilities that follow from this unitary treatment.

Importantly, the introduction of indexicalization into the best system should not be understood as the introduction of any unwanted subjectivity into the theory in any way. It does not imply that quantum probabilities are merely subjective, as per Quantum Bayesianism [76]. The Born probabilities reflect the objective chances of outcomes of interactions as grounded in the actual frequencies of such

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[20] It may be worth noting that such claims could be seen as direct consequences of the theory by means of Lewis's Principal Principle, for example. (See [75].)

outcomes in the mosaic (given the desire to balance strength and simplicity, of course, as discussed above). It also does not imply a subjectivity of the best system due to (1) the standards used to compare and evaluate systems (as raised by Armstrong, mentioned above), (2) the language in which our laws are formulated (as demonstrated in Goodman's 'paradox' [77].[21]), or (3) the subject matter or context in which the systematization is being developed (as discussed by Cohen and Callendar [78], as well as Bialek [69].)

The idea, rather, is that the introduction of indexicalization into our best system permits an *objective* perspectival dependence of how systems evolve. It may be true that Alice and Wigner disagree about the state of Alice's lab after she measures her qubit, but we can now explain that this is because the laws of nature require a 'point of departure' - a perspective from which they are applied.

Thus, the neo-Humean approach so far is quite fruitful in that it looks to provide a template into which perspectival fundamental physics can fit quite easily. Of course, there remains more for us to do here – we haven't yet established a means of validating (or perhaps better, vindicating) our causal intuitions. For this we turn to the mosaic, where we now have more than enough to establish certain constraints on the perspectivalist ontology.

3.5 The mosaic

Lewis's mosaic, recall, is a collection of local properties or states at spacetime points. It would be immensely convenient if such a mosaic could serve as the

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[21] See also [78].

supervenience base for the perspectival theorist, but it is not clear that things are this easy.

The worry can be seen in the following: say some measurement obtains a position state for some particle. The perspectivalist's position is to explain that from the point of this measurement onward, further measurement predictions should be dictated by evolving the system unitarily from this outcome – i.e. from the system being in the eigenstate corresponding to the observed measurement result. A simple, perhaps naïve way to combine this with the Lewisian ontology is to assume that this result represents a property in the mosaic. That is, at the time the measurement was taken, the particle's exact position is recorded as an event in the mosaic. The problem with this picture is that position eigenstates are 'improper'. They are not normalizable, and hence not physically realizable in quantum mechanics. (See [25] for some discussion.) As such, it seems that to pursue a mosaic composed of exact, determinate states (i.e. states with exact property values, such as position, energy, etc.), requires admitting a severe disconnect between ontology and physics. That is, it is not merely that quantum mechanics merely provides an incomplete description of the underlying ontology. Rather, it would be that quantum mechanics explicitly denies the true ontology from being physically realizable. To hold such a view would then require an explanation for (1) how an ontological state with exact, determinate properties can be associated with an (ideally, unique) quantum state (from within a perspective, in our context), and (2) how we actually get from our measurement outcomes to the correct quantum state when we subsequently apply quantum mechanics.

(That is, is there some dynamical explanation for this transformation within the quantum formalism? Does the best system simply tell us to use the associated state from the start? Etc.)

Admittedly this picture is a straw man – in what follows I will conclude by describing a mosaic that faces some of these issues. However, I cannot justify even beginning to defend such a view without first demonstrating trouble with the other options available. That is, we need to consider all other forms the mosaic might take before we consider a picture that requires us to re-evaluate how ontology and physics connect to one another. This task may seem daunting, but there is one way we might categorize the possibilities to ease the project. Thinking about what might compose the mosaic, there are two possibilities that are immediately on the table:

(1) a mosaic composed of exact, classical states (as in the case just considered).

(2) a mosaic composed of quantum states.

We might then categorize other options as one of

(3) 'both' (1) and (2) – states somewhere 'in between' quantum and classical.

(4) 'neither' (1) nor (2) – not states at all, but something else altogether.

(3) and (4) may seem entirely too vague to be of use but I will show that there is a single, clear option of the fourth type for the perspectivalist (though it will not prove very useful) and that the formal details of (3) are less important than we might think.

Going through these then: I have already mentioned difficulties that will be raised against a naïve attempt to posit option (1). Option (2) can be immediately rejected given the perspectivalist's rejection of representationalism. It makes no sense to deny that the quantum state represents the ontological state of a system while also admitting quantum states into your fundamental ontology. Moreover, even if such a position could be made coherent, this would demand the perspectivalist explain where single measurement outcomes appear in this picture. (In other words, we would be faced with a new, and more difficult version of the measurement problem.) Moving on to the third and fourth options then, I wish to address them in reverse order.

The fourth option is to deny that the mosaic is composed of states entirely. Although this suggestion may be entirely untenable on its own, the perspectivalist already has an alternative available: the mosaic might be composed of the properties determined by the single outcomes of measurements that she has posited to exist from the start. That is, rather than populate the mosaic with complete states, the perspectivalist might populate the mosaic only with those properties that correspond to the outcomes of realized measurements. For example, when Alice measures her qubit and observes $|0\rangle$, this result (*qua* property at a spacetime point, not state of the qubit) is the type of thing that composes the mosaic.

Now there are at least two ways that the perspectivalist might cash this out. She might explain that the properties selected by any measurement are those that exist in the mosaic as determinate values. Thus, in this case it is the qubit's computational basis measurement result at the spacetime point (or local region) of measurement that exists in the mosaic. Alternatively, she might take a 'pseudo-Bohmian' position and posit that all measurements are fundamentally position measurements (or perhaps measurements in some other privileged basis), and therefore it is only position properties that compose the mosaic.[22]

Indeed, this looks like a promising direction for the perspectivalist. Her project begins by assuming that quantum measurements result in single outcomes. To avoid solipsism these outcomes must exist in some objective sense, but this objectivity must somehow remain 'behind the veil' in other perspectives. By populating the mosaic with these outcomes, and then explaining that the best system for making predictions within the mosaic is that of quantum mechanics, the perspectivalist is able to account for both these claims directly. This said, there is are a number of related questions and difficulties with this 'interaction-based' mosaic:

3.5.1 Measurements vs interactions

First, if composing the mosaic with these measurement results, the perspectivalist must answer an important question which was asked above and postponed until now: what interactions count as measurements? There are, generally speaking here, two ways to go: either measurements are some special subset of interactions or all interactions can count as measurements. Neither of these options are ruled out, as far as I can see, but it worth consider briefly what each entails.

It is typically seen as undesirable to distinguish measurements from other interactions, especially by appealing to the size or complexity of the systems in-

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[22] Or more precisely, properties that amount to positions.

volved (as expressed by Bell in [19]). However, there may be principled reasons that could ground such a distinction (which may or may not have to do with size or complexity). For example, adopting the 'pseudo-Bohmian' position just mentioned, the theorist might explain that only those interactions which result (from some perspective) in localized position states should be classified as measurements. (This would be quite wide-reaching as the interaction terms in our Hamiltonians depend entirely on position.) Of course, this particular type of theory would qualify the types of properties that would appear in the mosaic but may not limit what types of systems may count as having a perspective. Two colliding fermions, for example, might be considered to measure one another in such a picture. (I mention this because it may be undesirable to some theorists to attribute perspectives to fundamental particles – they are not the types of systems that seems to 'observe' measurement results. There are not any fully described perspectival theories that seem to embrace this type of claim, but Bub has endorsed a view like this in personal conversation. Although I will raise significant difficulties with his view below, it is worth noting that in this context such a move is not nearly as difficult as it typically is.)

The standard concerns raised against quantum theories that distinguish macroscopic measurements from other interactions include, (1) that they reduce into a FAPP solution to the measurement problem (assuming they maintain the universality of unitarity), (2) that they demand some new dynamics of measurement, and/or (3) that they require some (otherwise unjustified) metaphysical distinction between macroscopic and microscopic systems. Note though that none of these worries apply to the perspectivalist approach considered here. Because she doesn't take the theory to be representational, the perspectivalist doesn't need to worry that she is neglecting interference terms as FAPP solutions do. She also has already explicitly denied that there needs to be any new type of measurement dynamics. And by composing the mosaic of measurement outcomes it isn't clear that she needs to worry about distinguishing macro and microscopic systems. That is, physical systems are merely emergent as part of the best system – they need not have any metaphysical weight in such a theory at all.

(One might pause here and wonder if I've snuck in some sort of vindication of a FAPP solution to the measurement problem. This is not the case at all though. The perspectivalist who claims that only certain interactions (i.e. those involving macroscopic systems) form an ontologically special category is not using this distinction to make any substantial claims about *what happens* during measurement. Her claims remain in line with those laid out by Bub and Pitowsky in [20]. She is now merely introducing a picture that allows her to make further claims about which systems might act as those with perspectives and which may not.)

The theorist may alternatively admit all interactions into the mosaic as measurements. There are some interesting questions here that may be worth investigating, but which I will not discuss in full detail. For example, given standard physical reductionism, one might think that the theorist ought to populate the mosaic merely with interactions between elementary particles. But doing so, it isn't clear how we might point to the results of what we typically call quantum measurements – interactions between a quantum system and a complex measuring device. The theorist likely has some choices here. She might associate the properties determined by macroscopic interactions with collections of properties determined by microscopic ones. She may even reject this reductionism and add the properties selected by these interactions. I see this question as parallel to those raised in the literature on mereology, and so I trust that the perspectivalist may turn to this to develop various details of the view.

Now these questions may highlight hurdles for an interaction-based mosaic but they do not present any arguments against it *per se*. There are two difficulties for the view that demonstrate far deeper trouble, however.

3.5.2 An insufficient ontology

An immediate difficultly with the interaction-based mosaic is simply that the associated ontology seems too impoverished. This may not be apparent when we imagine systems continuously interacting with each other as this makes such a mosaic appear to be densely populated, but imagine a case where some particle interacts with another and then evolves as a free particle for some period before interacting with another. We typically describe this by talking about the particle persisting between its interactions. However, if we take the mosaic to be composed merely of properties selected through interactions then it doesn't seem like there is any continuous set of properties that we might associate with the single particle. In Lewis's mosaic it is easy enough to do this by identifying systems with continuous property values that form world-tubes in spacetime. For example, we can explain that electrons are world-tubes where each time slice of the tube has the property of containing a charge of e^-, a mass of m_e, etc.[23] However, in this interaction-property mosaic there are no such continuous world-tubes. Rather we have very localized 'flashes' of property assignments at spacetime points or regions. Moreover, if we take the mosaic to be composed of properties selected by measurements, and these measurements can pick out non-commuting observables, then we may not even be able to look for continuity between the (sparse) properties in the mosaic at all.

This alone doesn't present a 'knock-down' argument against this type of approach to describing the mosaic. The theorist can probably develop a theory that reduces all systems to objects that appear only in the best system (despite their lacking ontological import). In fact, it isn't entirely strange for the best system to represent objects that don't exist in the mosaic. Forces, for example, are presumably not the types of things that exist in Lewis's mosaic (beyond, perhaps, in field potentials).

The deeper problem with such a view is that it fails to achieve that which we set out to do in the first place, which was to identify a metaphysics that will allow us to decide on the truth or falsity of counterfactual claims. This is because it is very easy to find cases where counterfactuals' truth values are indeterminate,

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[23] Presumably we might also describe the mosaic by introducing primitive systems, namely fundamental particles. In this case such an identification is trivial. Insofar as we might take the fundamental particles to be stand-ins for collections of property assignments, such as mass, charge, etc., though, I take the view presented to be ontologically 'cheaper'. Note that this isn't a novel ontological picture. See Timpson and Wallace [79] for a recent discussion of such an approach.

even given the best system and all the information of the mosaic. To see this, consider such a mosaic and imagine that the results of position measurements on (what we want to call) electrons populate the spacetime points s_1, s_2, s_3, and s_4 (as shown in fig. 3.1). Even if we assume that we can identify these as the positions of two evolving electrons (as compared to 4 individual ones), if there are no other interactions that occur in this region then it doesn't seem possible to distinguish whether the electron at s_1 traveled to s_4 and that at s_2 went to s_3, or whether the electron at s_1 went to s_3 and that at s_2 went to s_4. But given this, it is unclear how to evaluate a counterfactual like "had another particle been at rest along the path from s_1 to s_3 (s_5 in fig. 3.1), there would (probably)[24] have been a collision at this point and, as a result, no position measurement result at s_3". Of course, without being able to avoid counterfactuals like this we cannot then evaluate the related causal claims we seek to explain.

This problem isn't limited to sparse events like those in this toy example. In this interaction-based mosaic, unless there is a true continuum of interactions to densely populate spacetime, there will always be a difficulty in evaluating counterfactuals for this reason. The perspectivalist is therefore left without any clear explanation for the truth of the causal claims we sought to verify.

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[24] I add this only because a quantum description would at best describe a probability for the electrons colliding, of course.

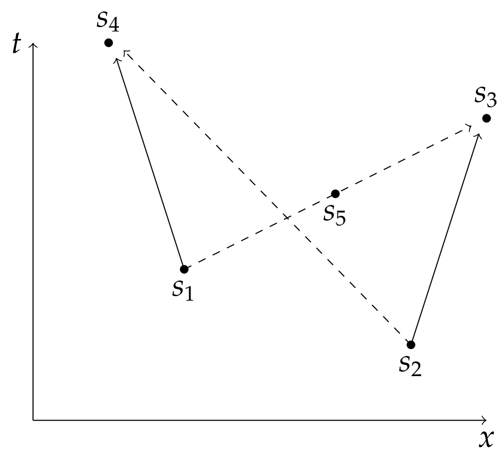

Figure 3.1: Four electron position measurement results in spacetime. In the interaction-based approach to building the mosaic, it is not clear how to differentiate whether the electrons travel from s_1 to s_4 and s_2 to s_3 (solid lines), or from s_1 to s_3 and s_2 to s_4 (dashed lines). This leads to indeterminacy about counterfactuals involving particles along these paths.

3.5.3 Ineffable ontologies

I take the problem just mentioned to be a truly knock-down argument against the usefulness of this interaction-based approach to defining the mosaic. There is one final option here worth considering, though. The perspectivalist may respond to this problem by diverging from Lewis's theory by enriching the mosaic with the addition of a fundamental system ontology. Doing so will allow her to avoid the trouble just presented as she will be able to ground the truth or falsity of the counterfactual in a combination of the mosaic and a fundamental fact about which electron goes where.

Bub seems to have described such a view, albeit one without the Humean backdrop. He explains that the true ontology of the universe is one that is not describable (let alone comprehensible) in Boolean terms, and that measurement outcomes are then genuinely random events that force this non-Boolean ontic state through a Boolean 'filter'. This is somewhat explained in [8]:

> A quantum 'measurement' is not really the same sort of thing as a measurement of a physical quantity of a classical system. It involves putting a microsystem, like a photon, in a macroscopic environment, say a beamsplitter or an analyzing filter, where the photon is forced to make an intrinsically random transition recorded as one of a number of macroscopically distinct alternatives in a macroscopic device like a photon detector. The registration of the measurement outcome at the Boolean macrolevel is crucial, because it is only with respect to a suitable structure of alternative possibilities that it makes sense to talk about an event as definitely occurring or not occurring, and this structure – characterized by Boole as capturing the 'conditions of possible experience' – is a Boolean algebra. [8, p.3].

Bub is here citing Boole [80, p.229] via Pitowsky [81]. Looking to Pitowsky's paper we see an insightful distinction between the quantum and the classical.

> In quantum mechanics we do not and cannot have a classical probability distribution from which to recover the expectation values of all the observables. This means that the relative frequencies of microphysical events (which are usually measured in several distinct samples) sometimes violate some of Boole's conditions associated with these events. [81, p.98]

Thus, the quantum state *qua* source of Born probabilities does not admit any a coherent description that provides consistent 'conditions of possible experience'. Such conditions are only available once we conditionalize on a set of commuting observables. It is worth noting that, although not surprising, this observation has some formal grounding. Szabó proposed in [82] that the probabilities of outcomes of compatible measurements would always admit a classical interpretation. This "Kolmogorvian Censorship" hypothesis was then proven by Bana and Durt [83].[25]

Going back to the question of underlying ontology then, we have ontological states that are indescribable (and incomprehensible) in Boolean terms. In this sense we might describe the underlying ontology as *ineffable* (though admittedly Bub has expressed some concern with this description). There is nothing we can assert, learn, know or even conceive of the state without applying some Boolean filter (or Kolmogorovian censor).

Admittedly there is something very attractive about this view, despite its vaguely anthropocentric tone. However, I believe that there are three significant difficulties that such a view faces:

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[25] Interestingly, this proof relies on an earlier theorem of Pitowsky [84] which provided the conditions for a set of correlations to admit a Kolmogorovian representation.

3.5.3.1 Instrumentalist concerns

First, it is unclear how to distinguish the resulting view from Quantum Bayesianism. The QBist position is that quantum probabilities give us (subjective) tools of prediction. As Fuchs and Schack explain, "[a] quantum state does not represent an element of physical reality external to the agent, but reflects the agent's personal degrees of belief about the future content of his experience." [85, p.2]. Admittedly, there isn't a clear description of the QBist ontology available. Fuchs presents some hints in [86] as well as in [85] with Schack, but it seems that the view wavers between some kind of a subjective, experiential ontology and a complete denial of an ontological state of the world.

The second of these resembles the 'ineffable' ontology I describe here. Insofar as a QBist denies objective ontology while also asserting the existence of an external world, it seems she must admit something akin to the ineffable states that Bub describes. (And if this is too strong, then it is certainly true that she *may* do so as a QBist.[26]) This is not to say that Bub is a QBist, of course. His view doesn't say anything about the subjectivity of quantum states or the Born probabilities, let alone Bayesianism. But insofar as the perspectivalist admits that is it possible for Alice's and Wigner's predictions to differ, it is unclear how to differentiate a perspectival theory with this type of ineffable ontology from a QBist one.

The natural option for this style of perspectivalist to distance herself from

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[26] Timpson [87] offers some further discussion on the ontology of QBism that is not far from this.

QBism would be to explicitly deny an agent- or observer-centric Bayesian element. Indeed, I've been speaking as if this were already the case, especially given the discussion in section §3.4 (insofar as I've said that the Born probabilities are objectively determined in each perspective). This approach begins to resemble Healey's pragmatic quantum mechanics. Healey explain that quantum mechanics is not representational but nor are the probabilities subjective: "The key difference [between pragmatism and QBism] is that while, for the QBist, quantum state ascriptions depend on the *epistemic* state of the agent who ascribes them, on the present pragmatist approach what quantum state is to be ascribed to a system depends only on the *physical circumstances* defining the perspective of the agent (actual or merely hypothetical) that ascribes it." [11, p.751].

However, bringing the view more in line with Healey's doesn't assuage the underlying problem of Bayesianism, which is the concern that the theory is fundamentally instrumental. I should pause here to be clear about this concern as some (outside of the QBist community!) have argued that labeling QBism as instrumentalist is unfair. For example, Healey explains that "The QBist does not take quantum theory truly to describe the world: but (s)he does take that to be the aim of science – an aim to which quantum theory contributes only indirectly." [88, §2.2]. Timpson gives more detail to this point:

> Thus, the quantum Bayesian begins by adopting a form of instrumentalism *about the quantum state*, but that is far from adopting instrumentalism about quantum mechanics *toute court*. The state is, of

> course, not to be given a realist reading, it is construed instrumentally, or pragmatically, as concerning predictions only; but that is conceded at the outset of the programme. And it is conceded in order to serve realist ends. The non-realist view of the state is not the end point of the proposal, closing off further conceptual or philosophical enquiry about the nature of the world or the nature of quantum mechanics, rather it is the starting point. Thus, it would be misguided to attack the approach as being instrumentalist in character. There is certainly no assertion that the aim or end of science is merely prediction, that we should stop right there. Given the hypothesis that the world precludes descriptive theorising below a certain level, to turn away from literal realist readings of one's best fundamental theory is not to turn away from realism, but to seek the only kind of access one can have. [87, p.592-3].

I have trouble with this analysis, however. Specifically, I don't see how the QBist anti-realism about the quantum state *doesn't* amount to "instrumentalism about quantum mechanics *toute court*" without an explicit explanation of the "indirect contribution" that Healey mentions. In fact, this is reinforced by looking to what Timpson raises after the above passage regarding the explanatory power of QBism:

> [I]t is hard to see how, if the quantum Bayesian approach to quantum mechanics were correct, we could have the kinds of explana-

tion involving quantum mechanics that we certainly do seem to have. . . . Thus think of the question of why some solids conduct and some insulate; why others yet again are in between, while they all contain electrons, sometimes in quite similar densities. To answer this question, we need to talk about the behaviour of charge carriers in bulk solids and what influences it. It presumably will not do to be told how, for example, by conditioning on data, independent agents who have certain beliefs about the constituents of sodium might come to have high degrees of belief that matter having that structure would conduct. This might be revealing if such reflections on beliefs could be read as a circumlocutory way of talking about facts about sodium in virtue of which one's beliefs would be justified; but in the quantum Bayesian picture, that is disallowed.

The central point is this: Ultimately we are just not interested in agents' expectation that matter structured like sodium would conduct; we are interested in *why in fact it does so*. The normal quantum mechanical discussion proceeds by reflecting on how the periodic structure of ions in a solid influences the allowed electronic states, opening up gaps (band gaps) in the energy spectrum of the allowed momentum states. Then one considers the location of the Fermi surface: the surface in (crystal) momentum space below which all the filled states lie. If this surface cuts a band of allowed states, the material will be a conductor as there are higher energy states for electrons to move into on appli-

> cation of a potential. If, however, the surface falls into a band gap between allowed states then the material will either be an insulator or a semi-conductor depending on the size of the gap to the next lot of allowed states. Now how much of this talk would remain as explanatory if we were to move to the quantum Bayesian position where there are no facts about what the states of electrons in a solid even are? [87, p.600-1].

The problem is the following: Given, as Timpson says here, that QBism cannot provide the explanations that we seem to look for (and find in) quantum mechanics, what is there left in quantum mechanics for the QBist to be non-instrumentalist about? It may be that QBism doesn't entail instrumentalism about science more generally but I don't see how she could avoid an instrumentalist interpretation about any statement in quantum theory if all statements must be cashed out in terms of agents' credences at the end of the day.

Healey's pragmatism may *seem* to avoid this problem insofar as the probabilities it describes are not Bayesian. However, he doesn't explain how he intends to avoid instrumentalism in his view. In fact, footnote 19 of [11] notes that a referee raised an argument against his view that parallels Timpson's complaint against the explanatory power of QBism. (As the footnote says, "Certainly, the spectacular success of quantum theory derives in large part from the way it helps us explain an extraordinarily wide variety of phenomena outside as well as inside the laboratory that at first sight have nothing to do with the statistics of measurement outcomes.") Healey includes a promisory note that he will address the issue in a subsequent publication, but I haven't seen such a paper in print.

I should add one note before moving on to the next difficulty with the ineffable ontology perspectivalist. She may, in fact, have a good way to distinguish her view from Healey's (which also avoids the problem of instrumentalism), though some more work will need to be done here. Because Healey doesn't take quantum mechanics to be foundationally applicable from only one perspective, he explicitly denies that probabilities can be grounded in a Lewisian mosaic. Specifically, he argues that this follows from a Lewisian demand that "the chance of an event . . . is uniquely defined at any given time." [11, p.755] (combined with an assumption that the Born probabilities will adhere to the Principal Principle). However, the perspectivalist has essentially already denied this detail of Lewis' original theory with the introduction of an indexicalized best system. That is, we find that we can only speak of the Born probability of an event *within a perspective*, not across them. Given this, it may be that our perspectivalist can avoid the instrumentalism that comes with these views by looking to the Humean analysis provided here for explanatory power. Note that doing so, however, may strongly commit the perspectivalist to adopting this pseudo-Lewisian metaphysics.[27]

3.5.3.2 Passing the Buck

Second, there is a worry that Bub's view is 'passing the buck'. Recall that one of the first conclusions we came to was that the perspectivalist cannot take the

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[27] This is permitted, of course, but I don't wish for it to be required.

theory to be representational of ontological states. But given Bub's description of the true ontological state as ineffable (in Boolean terms) it becomes unclear how much ground his view has actually gained.

Recall the motivation for the view: Given an encapsulated measurement, be it invasive or not, it looks that Alice and Wigner have divergent quantum descriptions of Alice's lab after she's made her measurement. Assuming we wish to maintain that the theory can be used correctly by both Alice and Wigner, that we deny the quantum state to be representational, and that we wish to avoid solipsism and instrumentalism, we are all but forced to deny that system's ontological states can be described completely by a Boolean algebra. The underlying system ontology is not be conceivable in the language or "conditions of possible experience".

This option may appear to answer this sort of perspectivalist's need, *prima facie*, but putting the view under further scrutiny we find that this is a false comfort. By claiming that the underlying ontology is ineffable the theorist is forced to admit either (1) that there is no connection between a system's true ontological state and the result of measurements upon it, or (2) that the underlying state turns out to be identical to the quantum state. In either case it becomes unclear how this ontology can improve upon taking the quantum state to be representational of ontology.

To see why, consider fermionic spin measurement statistics. (All that follows would equally well apply to more complex measurements of appropriately related observables on a more complex system.) Measuring an electron to be in $|z+\rangle$, if we perform an x-spin measurement on it and observe the result $|x+\rangle$ then we know there is a 50% chance of observing the result $|z-\rangle$ on a subsequent z-spin measurement. The question we need to ask is how these results relate to the underlying non-Boolean ontological state of a fermion. In answering this, the theorist is immediately faced with a dilemma. On one horn, she explains that the underlying ontological state changes when the +/- measurement is made. On the other she denies this:[28]

First, if she denies that the state changes then she is forced to say that not only is the entire state indescribable in Boolean terms, but that individual properties may not be so either as the single unchanged state must simultaneously give rise to multiple probability distributions of a single measurement. For example, here, the state must simultaneous give a 100% chance and a 50% change of $|z+\rangle$.

I should emphasize that this itself doesn't immediately pose a problem for Bub's view. He focuses on the impossibility to consistently combine the Boolean subalgebras that are selected by possible measurements. This doesn't necessarily require that the individual subalgebras are themselves consistent though. More abstractly, the fact that the entire state is fundamentally not describable in terms of a Boolean algebra doesn't at all imply that any subset (including singletons) of properties that compose the state should themselves be consistently describable in a Boolean subalgebra. The problem is that if we accept such a position then we are immediately forced to ask whether there is any connection at all between the underlying ontological state and the probabilities of measurement results.

Put another way, we might picture the underlying state as a multi-dimensional,

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[28] Bub has told me that Bohm raised a similar, if not identical point in their personal discussions.

highly abstract version of the duck-rabbit optical illusion, or perhaps even better, Matthieu Robert-Ortis's sculpture, *La Révolution des Girafes* (fig. 3.2). From one direction, d_0 the sculpture depicts and elephant, from another d_1 it depicts two giraffes. Analogously, we might think that selecting a measurement basis is like choosing a direction from which to look at the system. Just as we cannot look at the sculpture from any two directions at once, we cannot measure two non-commuting observables simultaneously. Of course, we would typically note that the analogy fails when we consider the nature of quantum probabilities. We might say, for example, that when we look at the sculpture from d_1 to see an elephant and then rotate to d_2 to see the giraffe, it is as if the sculpture changes so that we are no longer sure what's depicted from d_1.

Now the problem is that taking the state to remain unchanged through measurement is to say that the actual state of a quantum system is more like Robert-Ortis's actual sculpture than we think – it is 'set in stone' (if you'll excuse the pun). But if this is the case then there's no room for the probabilities of a given measurement's results to change – even after measurements in other bases. As a result, we're either left with a local hidden variable theory (with all the problems that come with them), or the theorist has to give up that the ontological state of the system is at all related to the probabilities of measurement outcomes. Recall, though, that for this sort of perspectivalist the Born probabilities were meant to reflect the ontological state through a Boolean 'filter'. If she gives up the connection between the ontological state and the Born probabilities then this picture falls apart entirely.

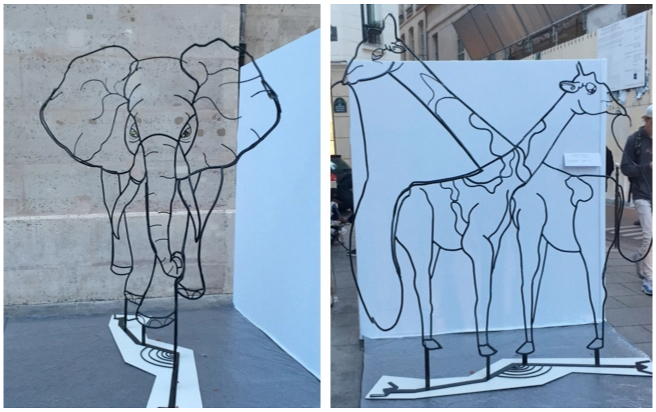

Figure 3.2: Matthieu Robert-Ortis's *La Révolution des Girafes*. (Image credited to Robert-Ortis.)

The other possibility is that the state does change upon the +/- measurement. In this case it isn't clear what this ontological picture achieves: Assuming (1) that the state changes upon measurement (or upon interaction more generally, perhaps) and (2) that the state gives rise to the Born probabilities, the distinction between the quantum state and this ineffable state fades away. There isn't anything left out of the ontological state by a fully representational interpretation of quantum mechanics. But if this is so, then avoiding contradictions (such as those raised by Frauchiger and Renner) by denying the representationability of quantum mechanics can only serve to 'pass the buck' from the quantum physicist to the quantum metaphysician. The same problems remain – they are merely swept under the rug.

3.5.3.3 Perspectival ontology

A final worry with the interaction-based approach, which is somewhat related to the second, is that the view is forced into a perspectival ontology. This may not seem problematic at first – after all, I'm defending perspectival quantum mechanics! – but I have maintained that one goal of the perspectivalist is to avoid solipsism. She does not wish to be forced into a position where the ontological state of the universe depends on her perspective from which it's described. Rather, she wishes to provide a theory that explains why scientific predictions might be perspective-dependent in a universe that has a single, objective physical state.

The difficulty can be seen by considering encapsulated measurements. Again, take Alice to make a measurement in an isolated lab and Wigner to treat her as evolving unitarily. If Wigner's use of quantum mechanics is correct, this implies that Alice's true state is ineffable – it cannot be understood in Boolean terms. However, from Alice's perspective things are quite different. Certainly *her* experience of her state meets the "conditions of possible experience"! But given this discrepancy, there are only two possibilities. Either Alice's experience is correct and her ontological state can be described in a Boolean algebra from her perspective, or she is incorrect and has limited access to her own state. [29]

It may seem that we can avoid solipsism by simply adopting the latter option and accepting that a system cannot have access to its own ontological state. However, to grant that Alice doesn't have access to her own ontological state is to call into question our fundamental assumption that quantum measurements have single outcomes. Once we allow that an observer has limited access to her own

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[29] Note that access to one's ontic state is very different from access to one's quantum state (as described in another perspective). I mention this as I will argue for the latter in chapter 4.

state, we are forced to acknowledge that she might be mistaken about what she observes in general. Indeed, this is precisely the position taken by many-world theorists. Thus, if we wish to maintain our central tenets, it follows from such a view that the ontological state must be perspective-dependent in this picture, which is a conclusion we sought to avoid.

3.5.4 Quasi-classicality

The above doesn't present anything like a formal 'no-go' theorem for interaction-based ontologies (if such a thing were possible). However, I don't see how one might get around these difficulties without diverging from the fundamental perspectivalist project altogether. This then brings us to what appears to be our last option: a mosaic composed of quasi-classical states. I haven't yet given an adequate description of what I mean by this, so I will begin by doing so.

I mentioned above that classical states were a non-starter because position and momentum eigenstates are improper, and therefore unphysical, according to quantum mechanics. Let us 'quantum-ify' classical states then by spreading position and momentum over a continuous region in configuration and momentum space, respectively, (so as to avoid delta functions in Hilbert space) but without concern for Heisenberg's uncertainty principle.[30] That is, we imagine the state to be spread in phase space but permit the spread in both position and momentum to both be very small. Thus, each of the two properties can independently describe

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[30] Or more precisely, without regard to the fact that position and momentum are Fourier transforms of one another in quantum mechanics.

quantum states, though the state as a whole does not. We can add to these states properties associated quantum observables that have no clear classical analogue if we wish (such as spin) as their eigenstates are not improper. It may not yet be clear why I raise the possibility of such a type of state. For the moment though, consider this only a test of our 'last option'. We have ruled out populating the mosaic with classical states, quantum states and measurement results (with and without an ineffable state ontology). As such the quasi-classical mosaic is the only option left.[31]

There is an immediate benefit to positing this quasi-classical mosaic: it permits a clear identification of measurement outcomes with ontologically 'realized' properties while simultaneously explaining what we observe at the macroscopic scale – and it does so without attributing properties that are (individually) unphysical according to quantum mechanics. There is quite a bit to unpack here, so an example will be helpful.

Consider the case of Alice making a position measurement on a single particle. (I am not considering spin measurements here only because, as mentioned, spin states are not improper eigenstates.) Posit that all of the fundamental particles involved in the measurement are in quasi-classical states, including the particle that Alice will measure as well as those that make up Alice, her mea-

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[31] The Lewisian mosaic is fundamentally composed of properties, not states. Translating between them is easy when considering classical properties. Here we would have do so some work, though this wouldn't be difficult. There are likely a few ways to do so: We might describe properties as applying to small regions, not points. We might define the properties of the mosaic as determining the centers of the regions at which the state appears. We might even add higher-order properties to the mosaic to reflect something like a spread of a single property value over spacetime regions.

suring device, and the rest of her lab. We will assume that the spread of each particle's state in phase space is small enough that Alice does not notice it simply because she is unable to observe such a microscopic 'fuzziness'. This includes, of course, the spread of the particles that compose her. From her point of view, she is in a classical state (or at least one that adheres to Boolean logic), albeit one that cannot be determined down to the Planck scale. By Heisenberg's principle, we know that her position basis measurement must include some finite uncertainty, and so for the moment assume that this uncertainty is greater than the actual spread of the particle's state in configuration space. In this case, Alice's result (1) doesn't demand that the particle ever have a pointlike position, and (2) can be understood as reflective of the actual ontological state of the particle, albeit not a perfectly accurate one. That is, if her uncertainty is larger than the particle's spread in position space, she can truthfully say that the particle was indeed in the region represented by the outcome of her measurement.

There are some interesting consequences of such a view. For example, it entails that Alice's (Boolean) experience of her state is both correct *and* inaccurate. It is correct in that she can ascribe to her state a nearly exact position and momentum simultaneously, but it is inaccurate in that the values she ascribes cannot be more exact than the spread of the ontological state.[32] The theorist may also now be able to talk about perspectives in more detail. That is, she might explain that while all systems are quantum systems, and there is no metaphysical distinction between a

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[32] Note that this isn't as strange as it may sound when we think about macroscopic systems. We know that the boundary of large systems are already a bit fuzzy when we get to the microscopic scale due to molecular motion and the position indeterminacy.

quantum system and an observer, it is only systems that are unable to distinguish the true ontological state from a classical state that should be considered as having a perspective. That is, Alice has a perspective that observes single measurement outcomes because her size and complexity are such that the ontological spread is unnoticeable. At the same time, electrons may be small enough that such a spread would be very 'apparent' to it (excusing the anthropomorphization), and so it doesn't make sense to speak of the electron's perspective.

There is more to say about what this ontology may look like, but before I go on I should address a few concerns that will be raised. First, one might be worried about assuming that we can posit position and momentum to have such small spreads in phase space. More to the point, how can we assume that Alice's measurement uncertainty will be larger than the spread of the particle's state in position space (or that the spread is too small for her to notice). After all, Heisenberg's principle demands only that the uncertainty of position and momentum *each* be greater than zero. It has no further constraints on their individual magnitudes, and in particular doesn't provide any maximum accuracy of measurements on either. However, if we're assuming that ontological states are fundamentally fuzzy, then such a constraint could follow from this ontology alone, not from the uncertainty principle: Say the spread of a particle's ontological state in position space is some value $\Delta x \ll \mathcal{O}(\hbar)$. In order to measure position with an uncertainty less than Δx would require a measuring apparatus which, itself, could differentiate between its being at two points in space less than Δx apart. But if all particles' states are spread in position space no particle would be able to do this (and so nor would any measurement apparatus). For example, if a photon is being used to measure position of some particle, but the photon's position itself is not localized in a region smaller than Δx, then the photon cannot 'record' whether it comes into contact with the particle at x_1 or $(x_1 \pm {}^{\Delta x}/_{2})$. As such, the assumption is easily defended.[33]

Second, one might stop here to note that we have no direct evidence of this type of ontology at all, and so positing it seems unjustified. However, let us recall how it is that we arrived here to see that this is not completely *ad hoc*. We wished to develop a consistent, single world theory that maintains the completeness and correctness of quantum mechanics. This has been achieved so far without any change to quantum mechanics and with only minimal changes to established metaphysical theories, namely the introduction of indexicalized content into the best system of laws – a move that turns out to be closer to standard best system account that might be thought given 'chancey' laws of nature. We are, therefore, in a good position to weigh the possible ontological models that might work given this, and insofar as we with to avoid solipsism and instrumentalism while maintaining the fundamental tenets of the perspectival position, we find ourselves in the position I've outlined here.

It might also seem troubling that this ontology seems so far afield from classical physics. But taking physical states to be highly localized can fit well with

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[33] Just to be clear, the thought is that any maximal accuracy that could be achieved in a quantum measurement is determined by the ontological spread in the quantum state (which could be far smaller than we have yet achieved in our experiments), not the uncertainty principle. Heisenberg's principle would then operate on our measurement results to describe a the unitarily evolving quantum state (in the perspective of the experimenter).

our experience of macroscopic systems as long as the spread of the ontic state is very small compared to the scales we observe. We then explain that quantum mechanics correctly describes, from one system's perspective, the probabilities of interactions with other systems. In most cases of interacting macroscopic systems this fits perfectly well with observation, as decoherence theory permits the quantum state to remain highly localized in Hilbert space over time.[34] It should be emphasized here that in this picture the classicality of our macroscopic observations does not have a 'life of its own'. Rather, it is a direct result of the fact that the universe (including its subsystems) evolves along what we might call a single branch of the wave function, and that as each branch evolves it demonstrates classical dynamics. To reinforce the point, if a quantum measurement were to obtain a result different from the result that actually occurs, the macroscopic systems that become entangled with that result would observer their own classical evolution at the macroscopic level. But this classical evolution is merely the result of underlying unitary dynamics that produces classical-looking correlations on each branch. When Alice's device measures spin-up, Alice observes it to have observed spin-up, etc. (Of course, in encapsulated measurements we isolate macroscopic systems from decoherence effects in theory, at least. In these cases, macroscopic systems don't observe classical behavior, but this is only because the highly 'volatile' quantum probabilities, which are usually only noticed when measuring very small systems, cascade up to larger scales.)

Putting these initial concerns aside then, a natural question to ask is the shape

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[34] See Wallace [41, §3.5-3.6].

of this spread. If we look just at an ontological state's position in one dimension, for example, does it form a continuous wave function with non-zero amplitude everywhere? A Gaussian (or other peaked) wave packet that cuts off at some distance? A square wave over some finite region? Etc. We might try to argue for or against certain options. For example, we might note that square waves require infinite potentials, which are unphysical. However, at the end of the day we have no reason to think that constraints from quantum mechanics must apply to our ontological state. (After all, we've already violated Heisenberg's principle.) All we require from this quasi-classical ontology is that individual properties can function as states which will then evolve according to quantum mechanics. That is, we need the mathematical description of the spread to be normalizable and perhaps that unitary evolution takes them to Planck-scale wave packets very quickly. I mentioned earlier that the formal details of this view are less important than we might have thought. What I meant by this is that any details beyond these constraints will have no impact on the quantum descriptions of systems in any perspective (and may even be unknowable, in fact).

That said, it's worth taking a moment to see that these constraints can be met. Take, for example, a particle's position in one dimension to be a square wave packet over a distance a. (As it must be normalizable, this is equivalent to specifying its height as $1/\sqrt{a}$). Solving for the evolution of this wave function (in short timescales) is difficult, partially due to the discontinuities are the border of the initial wave. However, Andrews [89] has done so, demonstrating that a near Gaussian probability curve is achieved at times in the order of $\tau = ma^2/\hbar$. Given an electron with mass $m_e = 9.1 \times 106-31$kg in a region the size of the Planck length $a = 1.6 \times 10^{-35}$m, $\tau = 21.2 \times 10^{-67}$s, which is far smaller than Planck time (10^{-43}s) and so could easily suffice.

The true cost of this view, then, is that it seems to require that physical systems' ontological states are richer than those which play a role in our physical theories, which is admittedly novel in physics. I will return to this point, but for the moment allow me to simply make clear that this is perhaps not as surprising or problematic as it may appear when we consider how we have arrived here: In building the perspectival metaphysics we found quite quickly that all but counterfactual theories of causation seemed problematic for grounding the causal claims we wish to make while also explaining that the Born rule describes genuine indeterminism. To use such a theory of causation though, we need to be able to evaluate counterfactual conditionals, and for this we follow the standard Lewisian direction to Humean supervenience theory. But looking to this theory already suggests a possible divorce of ontology from physical dynamics because the relationship between the mosaic and the best system is merely one of supervenience. Nowhere does the Mill-Ramsey-Lewis theory directly demand that the best system *represent* anything that exists in the mosaic – it must only describe its patterns in a balance of strength and simplicity.

What this means, though, is that the ontology of the universe – the physical states of its systems – can be entirely distinct from the states described by the best system. An example will help demonstrate what I mean here. Imagine a universe composed entirely of what we call electrons, or at least particles with a mass m_{e^-} and a charge e^-, which behave in a way consistent with our physics (specifically Coulomb's and Newton's laws). Particles separated by a distance r in this universe would interact according to the force law

$$\begin{aligned} F &= \frac{Gm_{e^-}^2}{r^2} + \frac{ke^{-2}}{r^2} \\ &= \frac{Gm_{e^-}^2 + ke^{-2}}{r^2} \\ &= \frac{C}{r^2} \end{aligned}$$

where G and k are the gravitational and Coulomb's constant, respectively, so $C \approx 2.307 \times 10^{-28}\mathrm{N} \cdot \mathrm{m}^2$. Now the best system in this universe need not give any more than the last line here – there is no reason to dissect C into its gravitational and electrodynamic parts. Thus, in this universe, just as in the picture I've drawn here for ours, there is a richer ontology than the best system describes, and moreover, the constant C that appears in the best system represents nothing in the actual ontology.

Let us take stock then. Beginning with a perspectival view, I have outlined the (somewhat surprising) metaphysical constraints and implications that come from considering non-invasive measurements in a perspectival quantum theory. First, I have argued that given some very intuitive causal claims that arise in the context of such measurements, the theory is all but forced to accept a counterfactual theory of causation. But such a theory demands a semantics of counterfactuals in order to hold. Fortuitously, the first advocate of (contemporary) counterfactual theories of causation, David Lewis, gives us a method of building this semantics that outlines how we can build our metaphysics, clearly delineating between our ontology and our physics.

Following this path, we have seen that taking quantum physics as our best system, we can develop a mosaic that provides what we require, although part of the reason for this success is the distinction between the ontological state of the mosaic and the metaphysical picture that *seems* to be drawn by the best system. More specifically, taking the Lewisian approach means that we do not need to take quantum states to be ontological representational. This is precisely in line with how we began, following Bub's argument that a single-world (non-Bohmian) theory must take quantum mechanics to be probabilistic.

Before moving on to consider invasive measurements there are some final points to be considered and clarified: First, for the sake of clarity I will provide a detailed toy model of the non-invasive measurement scenario, demonstrating how the view outlined here addresses the situation and provides the intuitively correct truth values for the causal claims that we wish to claim. Second, concerns have been raised about the use of counterfactual conditionals in quantum settings, for example by Stairs [72]. I must, therefore, explain why these worries do not apply in the context I've given. Finally, as mentioned above, my intention here is not to force the perspectival theorist in a Lewisian corner. Rather, this is meant to be a 'proof of concept', demonstrating the possibility of a coherent (and consistent) theory. As such, I will conclude by discussing what precisely the theorist is committed to and what she may leave behind in order to avoid the (often notorious) title of "neo-Humean"!

3.6 A toy model

Having outlined all this, let us walk through how it comes together in the perspectivalist approach. To do this, we need to show how a model will provide the correct truth valuation for the counterfactual claims without falsifying other key elements of the position. Specifically, it should not inadvertently force the perspectivalist into a accepting something like a local hidden variable theory (or into a completely instrumentalist position), nor can it seek to differentiate or define possible worlds by looking to quantum state descriptions, as this would demand some sort of representationalism.

These last points will be of key importance here, as we will wish to describe the space of possible worlds in terms that are relevant to Alice and Wigner, and this will seem to require looking to quantum state descriptions. As I will explain, however, there is a clear path to using quantum states to explore possible worlds that avoids any trouble.

3.6.1 Proximity of possible worlds

To start then, we will consider the space of possible worlds from Alice's point of view, which is quite straight forward. After she has conducted her measurement, there are three relevant classes of possible worlds: Those in which the measurement results in $|0\rangle$, those in which the measurement results in $|1\rangle$, and those in which the measurements doesn't see either result.[35] The third class of possible worlds is included as a catch-all for all other possibilities that may appear in a more complex treatment of the measurement. For example, if Alice's measurement is a simple spin measurement with a Stern-Gerlach device, this might include the possibility that the particle tunnels through the screen. Similarly, treating the entire lab as a quantum system should include, presumably, the possibility of Alice making a measurement in another basis. I mention all three classes of possible world because explaining how this model will work requires at least some discussion of similarity between possible worlds. Specifically, I wish to argue that if the measurement result is a $|0\rangle$, there is good reason to believe that almost all of the worlds in which it results in a $|1\rangle$ are closer to the actual world than any of those in which neither result occurs, (and that those worlds that are further away will not impact the success of the model). This may seem to be an easy claim, but it is a bit tricky to navigate this position without accidentally falling into some sort of representationalism.

I don't wish to become drawn into the vast debate about how possible worlds may and may not compare to one another and so I will instead attempt to draw a picture from Lewis's discussion in [68] in a fashion that minimizes contention. Lewis argues that to evaluate a counterfactual claim of the form, "if P had been true then Q would have been true," we must go to the closest, i.e. most similar,

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[35] Note that I refer here to measurement results rather than to observations because I specifically with to point to worlds described by the unitary evolution of the measurement without considering, for example, how this result decoheres into the lab environment. Thus, what matters is the state of the measuring device at the end of the interaction, not how this state is observed by Alice. Everything concluded here can then be easily (if not trivially) restated with consideration for this 'encapsulated decoherence'.

P-world (or P-worlds) and evaluate whether Q is true there. Assuming P is false in the actual world, Lewis describes the closest possible P-worlds as those that share the same history as the actual world up until a "small miracle" results in the truth of P. Assuming that the laws of nature are deterministic, these 'miracles' represent limited (and spatiotemporally localized) violations of the (actual) laws of nature. [68].

The entire discussion of these Lewisian miracles is a difficult move in counterfactual semantics, but thankfully the perspectivalist can do away with this talk almost entirely. This is because moving from a world in which Alice's measurement results in $|0\rangle$ to one in which it results in $|1\rangle$, for example, need not involve any law-violating sequence of events. It is entirely consistent with the best system, as applied from Alice's perspective, that the measurement could have resulted in $|1\rangle$. Indeed, it is precisely because of this that she can make claims about the relative proximity of certain possible worlds without getting into the details of the similarity relation. She need only claim that worlds in which the laws are not violated are closer to the actual world than ones in which the laws are violated, which is completely in accordance with our intuition and with Lewis's original picture.

It might be thought that this permits us to rule out, right off the bat, a large number of possible worlds in which the measurement doesn't result in $|0\rangle$ or $|1\rangle$. However, it is somewhat tricky business determining which of these worlds, if any, require law violations when there is a sense in which the entire unitary evolution of the wave function is available to consider. That is, just as Alice might note that it is not a law violation for her measurement to have resulted in a $|1\rangle$ because this has a non-zero Born probability, she may equally note that there is a non-zero probability (in some perspective, at least) associated with the possibility of her having pressed the wrong button on her measurement device, or of the device suddenly breaking, or even of her molecules spontaneously rearranging into a bowl of petunias and a very surprised whale.[36] Thus, the perspectivalist must find some way to determine the relative proximity of possible worlds to one another without relying entirely on ruling out law violations.

It is worth discussing a natural 'first pass' attempt here, although it will fail quite quickly. One might think that the perspectivalist can appeal to the Born probabilities themselves to determine similarity, where higher probability indicates a higher degree of similarity. However, we can see why this is too weak by considering the possible worlds where the measurement doesn't produce $|0\rangle$ or $|1\rangle$. Consider, first, cases where the measurement fails. Say that prior to the measurement the combined state of the lab and qubit is such that if Alice makes the measurement there is some small but non-zero probability of some disruption to the measurement occurring, for example because another particle may collide with the qubit being measured, etc.. To assume here that the smallness of the probability of these failures reflects modal distance from the actual world is entirely question-begging. If we take quantum mechanics to be merely a Lewisian best system given the distribution of events in the actual mosaic, then there is no reason to think that its probabilities should be at all informed by the relative

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[36] Credit is due to Douglas Adams, of course, for this marvelous example.

proximity of non-actual possible worlds. Moreover, to take the Born probabilities as representing such a relation calls into question our non-representationalism at its core. Such a view may not take the quantum state to be representative of a system's ontic state in the actual world, but it does seem to take it as representative of some larger, 'cross-world' state of a system (and its possible world counterparts). This may not be entirely problematic given our original reasons for rejecting the representationalist view, but it does seem to imply that the theorist would be committed to some sort of modal realism, which is certainly more than we want to demand of her.

One might try to salvage this approach by considering considering quantum treatments of all systems involved, including Alice and Wigner, and then looking to intuitive cases to justify a Born rule-based distance measure. For example, worlds where Wigner is in the lab and Alice is the superobserver should be farther away from the actual world than those wherein Alice measures and observes $|1\rangle$, and so we might expect them to have a lower Born probability of occurring. The problem is this is entirely unjustified. We have no reason at all to assume that actual state of affairs is highly probable given a unitary evolution of the systems involved. Moreover, the probability of a given state can vary tremendously depending on how 'far back' we go. It's entirely possible that it's far more probable that Alice should be outside the lab and Wigner within it given a unitary treatment of Alice and Wigner since 8:00 am yesterday, and even if this isn't the case, it may be far more probably that Alice and Wigner never met given a unitary treatment from a point further back in time, or indeed, that they were never even born given some even further point in the past. Without a principled way to know when to start this unitary treatment of the systems involved there is no unique set of Born probabilities to look at.

Abandoning this probability-based approach then, we need some other way to arrive at a proximity or similarity relation. There may be multiple ways this can be achieved and so the one I will suggest here should not be taken as unique (nor necessarily generally correct, in fact – I am offering a toy model here, after all).

Intuitively, if world w_1 is more similar to the actual world w_0 than another world w_2, Alice should be able to *know more* about w_1 than she does about w_2. In other words, Alice should have access to more information about w_1 than w_2. One way we might cash out this is in terms of some distance between the actual and the possible quantum state Alice would use to describe the world around her. Although one might desire a fully formalized distance measure, it seems unnecessarily complex for my purposes here. Instead I wish to suggest a relation that is based on the following two definitions:

Say a system begins in some state at time t_0 and will evolve unitarily until time $t_1 > t_0$, when it will be measured to be in one of at least two states. Then: (1) if the system actually ends up in some state $|\psi\rangle$ at t_1, we will say that a possible world that is identical to the actual world up until the point t_1, at which point the system is measured to be in some other state $|\phi\rangle$, t_1-*diverges* from the actual world.[37] (2) In the event that the system is complex, we consider a state

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[37] Note that t_1 must be the time of measurement

description of the fundamental particles that compose it. We will then say that a non-actual world *n-differs* at a given time t from the actual world where n is the number of fundamental particles whose states are different from their actual ones. For example, if the system is a neutral atom with an electron that might be struck by an incoming photon at t_1, we consider a fine-grained description that includes the states of the quarks that compose the atom's nucleons, its electrons and the incoming photon. If the photon doesn't actually collide with the atom then the possible world in which the photon does collide with the atom 2-differs from the actual state at t_1, as the electron's and the photon's states will be altered. Of course, as time progresses and the other particles become entangled with one another in both the actual and possible worlds, n will grow very rapidly.

With these definitions then I offer the following two factors for determining the relative similarity between possible worlds: If w_1 and w_2 are possible worlds, and w_0 is the actual world, then w_1 is more similar (closer) to w_0 than w_2 if one of the following holds:

- If w_1 t_1-diverges from w_0 and w_2 t_2-diverges from w_0 such that $t_1 > t_2$.
- If both w_1 and w_2 t_1-diverge from w_0, but w_1 n-differs from w_0 at t_1 while w_2 m-differs from w_0 at t_1 for $n < m$

Each of these offers a partial ordering of possible worlds. The first says that worlds which diverge more recently from the actual world are closer than those which diverge further in the past. The second says that among those that diverge simultaneously, those with a fewest number of fundamental particles whose states differ from the particles' actual states are closest. Allow me to explain how these work and why both are required.

The first of these factors mirrors a claim made by Lewis. He offers here a list of priorities in deciding which worlds to consider when evaluating counterfactuals. First in this list is the avoidance of "widespread" law violations, which I have argued is not a problem for the perspectivalist here. Following this, "[i]t is of the second importance to maximize the spatiotemporal region throughout which perfect match of particular fact prevails." [68, p.472]. By defining as closer those worlds which diverge temporally later from the actual world, we ensure that the closest worlds maximize the spatiotemporal region in which the worlds agree. Note that this does not ensure that *all* worlds which maximize a spatiotemporal region that agrees with the actual world are considered closest to the actual world. It is easy to imagine a possible world that is exactly like the actual one but for the position of some fundamental particle at some point in the distant past. For example, had a single photon γ in intergalactic space spontaneously split into an electron-positron pair, which subsequently annihilated one another to emit a photon with same momentum as γ, this would almost certainly have absolutely no impact on the subsequent evolution of the universe. However, despite the very large spatiotemporal region in which this possible world agrees with the actual one, it is here determined to be less similar than one which diverges more recently but with much larger, macroscopic effects. This may seem unwarranted, but insofar as our purpose here is to find a reasonable similarity relation that reproduces our intuitions about certain counterfactual dependencies, we will see that this certainly proves adequate. (Moreover, I should add that there may be no genuine concern about possible worlds like the one considered. Insofar as γ would be treated as evolving unitarily by any other perspective, there may be no distinction between worlds where it splits and where it doesn't in Alice's valuation of the counterfactual.)

The second of the two factors may seem unnecessary – and likely would be in the context of a deterministic universe. However, given the indeterministic nature of quantum mechanics it is necessary to consider not just the spatiotemporal region in which a possible world agrees with the actual one. We must also consider "how different" two worlds are given that they diverge at the same time from the actual world. Consider, for example, that given the state of Alice's lab before her measurement there is a non-zero probability for the measurement device to very suddenly sublimate into a homogeneous gas at t_1 instead of her measurement taking place. It would be ideal if there were some way to quantitatively measure qualitative differences between states of affairs in order to say that this is a much more distant world than one in which she measures a different outcome. Rather than even aim for something so farfetched though, the factor I've given allows for at least an approximation of the intuition. That is, it ensures that possible worlds in which a smaller number of fundamental systems are different are considered to be closer than those which observe larger-scale deviations. Thus, after Alice's measurement is complete, we ensure that worlds which observe merely a change in the measurement result are closer than those which include spontaneous gasification of the measurement device. Of course, given that these factors only provide a partial ordering there will certainly be possible worlds that are equally similar (close) to the actual world, but I cannot imagine a case in which this would lead to a counterintuitive valuation of a causal proposition.

3.6.2 Counterfactual evaluation from Alice's perspective

Given these factors in determining the proximity of possible world we can see how Alice's evaluations of relevant counterfactuals come out as desired. Recall that in our non-invasive measurement scenario we want to capture the intuition that Alice's result causes Wigner's (from both Alice's and Wigner's perspectives). Assuming Alice's measurement results in $|0\rangle$ (and so Wigner's in $|A0\rangle$ for reasons we've seen above), the causal claim is true if the following counterfactual is true: "Had Alice's result not been $|0\rangle$, Wigner's result would not have been $|A0\rangle$." Following Lewis, to evaluate this we need to find the closest possible worlds where Alice does not observe $|0\rangle$ and then see what the laws of nature determine.

To do this, let's say the qubit is a fermion and Alice conducts her measurement with a Stern-Gerlach device oriented in the z-direction. In this case we might consider the time of measurement t_1 to be the time at which the qubit hits the screen, and we can describe its possible states at t_1 as $|0\rangle = \left|z+, y = 0\right\rangle$ and $|1\rangle = \left|z-, y = 1\right\rangle$ where y is simply a position on the screen. (Taking this to be the time of measurement is not arbitrary but rather guided by evidence from other experiments. For example, the double slit experiment tells us that we cannot ignore interference terms prior to t_1.) We might then note that if Alice's measurement occurs at time t_1, then there can be no worlds that diverge from the actual world after time t_1 in which her measurement doesn't result in $|0\rangle$.[38] And by our similarity relation we know immediately that if there are any worlds in which Alice doesn't observe $|0\rangle$ that t_1-diverge from the actual world, these are closer than any which t_0-diverge from the actual world for any $t_0 < t_1$. Therefore we need to consider t_1-divergent worlds to evaluate the causal claim.

Looking to these worlds, we know that they include worlds in which the measurement doesn't result in $|0\rangle$ as this is dictated by the Born rule. We therefore want to look to t_1-divergent worlds and identify those which minimally n-differ (i.e. those which n-differ for the smallest n). Of course, in the relevant t_1-divergent worlds the qubit measured must be in a different state than in the actual world, but let's treat this a little more carefully. If the fermion strikes the screen at t_1 and we describe that screen as a collection of fundamental particles, then we can say that there will be a 'first' particle (or perhaps set of particles) that the fermion collides with. Thus, in the t_1-diverging worlds where Alice doesn't observe $|0\rangle$ we find that there is at least a difference in the fermion's state as well as differences in the states of the particles that the fermion does or doesn't collide with.

Noting that there are t_1-divergent worlds which differ only with respect to these particles rules out all but two kinds of worlds. The first are those in which

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[38] Just to be clear, I am still referring here to Alice's measurement results rather than her observations because I don't want to worry about the possibility that something comes between the result and her observation of the result. A more careful treatment would take this possibility into account in exactly the same fashion as I will do here, and may, for example, explain that Alice can have the *false* belief that her measurement result causes Wigner's in such cases.

the fermion's state at t_1 is $\left|z-, y = 1\right\rangle$. In these worlds we can appeal directly to the universality of unitarity again to see that Wigner must observe the result $|A1\rangle$, and so the counterfactual holds. The second kind of world presents a slightly trickier case though. These are worlds wherein the fermion's state at t_1 is neither $|0\rangle$ nor $|1\rangle$, for example in the case where it tunnels through the screen rather than colliding with it. In these worlds Alice's measurement doesn't have a result at t_1 – the state of the fermion is indeterminate even in her perspective – and so we cannot be certain of Wigner's measurement result. I can see two ways we might approach these cases.

First, we might try to justify neglecting them entirely as there is a relatively strong intuition that they are not relevant in our causal judgement here. Consider a classical example: Say I tell you I will flip a coin and give you a book depending on the outcome – if it flips heads I will give you *The Hitchhiker's Guide to the Galaxy*, and if it flips tails I will give you *Dirk Gently's Holistic Detective Agency.* You receive a copy of *Dirk Gently*, and so you assume that the coin landed tails and that this result has caused your new reading material – had the coin not landed tails you would have received something different. However, when I flipped the coin I did so over a sewer grate and almost dropped it, and so it turns out that the closest possible worlds in which I didn't get tails are ones where the coin falls into the sewer. If I tell you this later you wouldn't think "oh, it turns out my causal judgment was incorrect." Rather, if you were to reconsider your causal judgment at all it would likely be to acknowledge that your initial counterfactual conditional had an implicit *ceteris paribus* clause attached to it. What you cared about were worlds where the coin toss landed on not-tails, not worlds where the coin toss didn't land at all. Taking this to our case we might apply the same logic and note that there is implicit *ceteris paribus* clause here too – what matters are worlds where Alice's measurement *has* a result and the result is not $|0\rangle$.

A second approach might be to look to Lewis's later work [90]. Here Lewis considers how probabilistic events might fit into his counterfactual theory and offers a revised definition for causation. An event C is said to cause E if the chance of E is significantly reduced in possible worlds where C doesn't occur. Adopting this revision allows us to say that Wigner's $|A0\rangle$ result is caused by Alice's $|0\rangle$ result because the chance of Wigner's outcome is far greater in these worlds than in any of the closest worlds in which she doesn't obtain a $|0\rangle$ result. This is trivially satisfied when Alice obtains $|1\rangle$. In cases where she doesn't obtain a result Alice can't be sure about what Wigner will observe (note that his measurement will now be invasive) and so it is necessarily the case that the probability of his measurement resulting in $|A0\rangle$ is higher when her measurement result is $|0\rangle$. ("Significantly" is not precisely defined here (nor by Lewis), but there is an intuitive sense, I think, that changing any uncertainty to certainty is significant.)

Regardless of which approach we choose, we have a relatively intuitive explanation now for why Alice can say that her result causes Wigner's. From here it remains to show that Wigner can make the claim too as we have conceded that it seems available to him regardless of the fact that must also deny the existence of a single outcome of Alice's measurement.

3.6.3 Evaluating from Wigner's perspective

The evaluation from Wigner's perspective is similar to Alice's. The only potentially worry is whether special attention must be given to Wigner's evaluation of the counterfactual prior to his measurement (as compared to after it) when, in his perspective, Alice cannot be described as having observed a result.

Consider the case after Wigner's measurement first. Wigner seeks to test the truth of the same counterfactual considered above (from his point of view): "Had Alice's measurement not resulted in $|0\rangle$, I would not have not measured $|A0\rangle$." Just as in the case considered above, Wigner can appeal to the universality of unitarity, and now treating Alice's measurement as having resulted in a single outcome from her perspective (given his result), pursue the same method as just described for Alice to determine the truth of the counterfactual. That is, for Wigner to acknowledge the truth of the counterfactual after he completes his measurement does not require him to also posit anything about Alice's result *prior* to his measurement. Knowing that quantum mechanics is perspectival, he can coherently state that while Alice's outcome doesn't exist in his physics prior to his measurement, she has observed a result in her perspective, and that what is observed in his perspective is counterfactually dependent on what she observed in hers.

However, in addition to this case there is the intuition that Wigner should be able to make the causal claim before his measurement. It feels like he should be able to say, "my result *will* be caused by Alice's," even though Alice's result doesn't exist in his perspective. The concern then is how Wigner can even entertain the possibility that Alice has observed a result in her perspective prior to obtaining his.

I think there are two possible answers here, both of which eliminate any concern. First, we might note that allowing Wigner to consider Alice as having observed a result counterfactually doesn't necessitate Alice to have actually observed a result at all. That is, before his measurement, Wigner may consider the following statements):

- "If Alice's measurement had resulted in $|0\rangle$, then (by the universality of unitarity), my measurement cannot result in $|A1\rangle$."
- "If Alice's measurement had resulted in $|1\rangle$, then (by the universality of unitarity), my measurement cannot result in $|A0\rangle$."

Prior to Wigner's measurement each of these are indeed counterfactual in his perspective as here it's false that Alice observed either result. These alone don't demonstrate the counterfactual dependence required to ground a causal relationship, though. To do so we'd need to add, for instance, a statement that Wigner's measurement must result in either $|A0\rangle$ or $|A1\rangle$ (which could follow from similar considerations to those mentioned at the end of the previous section).

That said, this approach does have a certain weakness in that the antecedents of the counterfactuals considered here do seem to involve a law violation, unlike those considered so far. That is, it cannot both be true that Alice evolves unitarily and that her measurement results in either of the two possible outcomes. As such, we might instead consider a somewhat more pragmatic route: We know that after Wigner's measurement is complete, he can claim that Alice's results causes his for the same reasons that Alice can do so. Why not, therefore, explain that when Wigner makes the causal claim prior to his measurement, he is merely expressing his knowledge that regardless of his result, the causal claim *will* hold. (His claim asserts a future causal claim, after all.)

In other words, I don't see any reason to treat this particular case as being any different from making other future-oriented causal claims. Consider the following: Andrew and Betty are playing a board game. Near the end of the game, as Betty picks up the dice, Andrew thinks to himself, "if Betty rolls a 12 that will cause me to lose." Such a causal relationship seems entirely natural, but the fact that Betty hasn't yet rolled the dice makes it somewhat tricky to demonstrate counterfactual dependence here. Without knowing what the actual world is like, it's hard to know what the closest worlds are. However, we might simply pursue the following line of reasoning: Andrew is in a position to know that if Betty rolls a 12 then the following counterfactual will be true in the future: "If Betty hadn't rolled a 12 then I wouldn't have lost." As such, it's possible for him to make the causal claim prior to Betty's roll.[39]

Taking this line to Wigner's case, it can be true that in Wigner's perspective there doesn't physically exist an outcome of Alice's experiment. However, Wigner

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[39] As Harjit Bhogal has explained to me, counterfactuals are often taken as tenseless and so there is not usually a concern about justifying future-oriented counterfactuals. Taking such a position makes my point here easier, of course. I include specific considerations about these cases here to offer a justification in case the tenseless view isn't adopted – especially given that the physical existence of Alice's result changes in Wigner's perspective.

is in a position to know, even before his measurement, that after his measurement it will be true (*ceteris paribus*) either that "if Alice's measurement hadn't resulted in $|0\rangle$ then mine wouldn't have resulted in $|A0\rangle$," or that "if Alice's measurement hadn't resulted in $|1\rangle$ then mine wouldn't have resulted in $|A1\rangle$." As such, Wigner has perfectly good reason to make the causal claim prior to his measurement taking place. Of course, it's possible that Wigner's measurement fails (or indeed that Alice's has failed in her perspective), but this doesn't raise any problem. It simply means that Wigner might be incorrect, just as any future-directed causal claim might be: It might be that Betty rolls a 12 but doesn't see the move that would beat Andrew, in which case we would simply say that Andrew's predictive causal claim was incorrect.

3.6.4 Generalizing to high dimensionality

The model given above has only considered the case of a two-dimensional measurement. It should be noted that the same methodology can be generalized to non-invasive measurements of arbitrary dimensionality.

Say that Alice makes some $n + 1$-dimensional measurement on a system in the basis $\{|0\rangle, |1\rangle, \ldots, |n\rangle\}$. The situation is exactly the same as the 2D case if Wigner then makes a measurement in the basis $\{|A0\rangle, |A1\rangle, \ldots, |An\rangle\}$ (where each $|Ai\rangle$ corresponds to Alice having observed $|i\rangle$). To generalize this, we will first consider the case where Wigner makes some $m + 1$-dimensional measurement on Alice's lab in a basis $\{|A0\rangle, |A\alpha\rangle, \left|A\beta\right\rangle, \ldots, |A\omega\rangle\}$, where all but the first basis vector (i.e. those labeled with Greek letters) are superpositions of all of $|A1\rangle$ through $|An\rangle$. In this case, Wigner's measurement will be invasive unless Alice's measurement results in $|0\rangle$. (Recall that whether a measurement is invasive might not be known to either of Alice or Wigner. Again, there is no physical or metaphysical distinction being made between invasive and non-invasive measurements. The distinction is only made to answer concerns raised against the perspectivalist. At the end of the day all measurements are equal.) Looking to this case then, let's consider what our intuitions are and whether the model can explain them:

If Alice believes that Wigner will be making this measurement (as she otherwise wouldn't have good reason to make any predictions, let along the causal claim!), then upon observing her $|0\rangle$ result she could say, "my result will cause Wigner to observe $|A0\rangle$." Such a claim seems to function in exactly the same fashion in Alice's perspective as in our initial case. In the closest possible worlds where Alice's measurement doesn't result in $|0\rangle$ it is impossible for Wigner to observe $|A0\rangle$, and so the causal claim holds.

In Wigner's perspective, however, things are slightly different. In the event that he observes $|A0\rangle$, it seems appropriate for him to claim that Alice's outcome caused his. However, if he observes any other result, the only causal claim that seems appropriate is that Alice's outcome caused him *not to* observe $|A0\rangle$. That is, he can't make the general causal claim that Alice's outcome caused his outcome as all of her other possible outcomes are consistent with all of his other possible outcomes.[40] What he can say, though is that whether or not Alice observes $|0\rangle$

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[40] I am neglecting Lewis's [90] incorporation of probability into the definition of cause here.

has a causal impact on whether or not he observes $|A0\rangle$. (Following the reasoning given above, this will be true for Wigner both before and after observing the outcome of his measurement.)

Now if we focus on this more limited causal claim then things can proceed as they did in our original case. After the measurement, if Wigner observes $|A0\rangle$ he can counterfactually see that had Alice not observed $|0\rangle$ he would not have observed $|A0\rangle$. If he doesn't observe $|0\rangle$ then he can go to worlds where Alice did observe $|0\rangle$ and see that he would have seen $|A0\rangle$. Looking to the more general causal claim, though, it's also clear why the required counterfactuals don't hold. If Wigner observes, say $|A\kappa\rangle$, he cannot say that had Alice's observation been different he would have observed otherwise. Indeed, in this case he can't even clearly speak of Alice's outcome, as the information about it is now entirely lost in his perspective as she is in a superposition of $|A1\rangle$ through $|An\rangle$.

This final point has not been pressed very much thus far and will be further discussed in the context of invasive measurements below, but it is clear to see why this is the case. Once Wigner measures Alice to be in some state $|A\kappa\rangle$ he must treat her as evolving unitarily from this state. This means that if he were to then measure her in the $\{|A0\rangle, |A1\rangle \ldots |An\rangle\}$ basis her answer might offer no information about what she actually did originally observe. Now this might bother some perspectival skeptics, but the concern can be put aside for now by noting that there is no reason to think that our intuitions about what Alice

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Including this is not at all problematic, but depends on the exact definitions of Wigner's basis vectors in terms of the $\{|A0\rangle, |A1\rangle \ldots |An\rangle\}$ as causal claims will then depend on comparing the precise probabilities of each of Wigner's outcomes given each of Alice's.

experiences are correct after she goes through the entirely exotic experience of being measured in the state $|A\kappa\rangle$.[41]

What is left to fully generalize to the higher dimensional case is to consider when Wigner's measurement basis is composed of any combination of vectors and superpositions of vectors from $\{|A0\rangle, |A1\rangle \ldots |An\rangle\}$. For example, say he measures in a basis $\{|A0\rangle, |A2\rangle, |A5\rangle, |A\alpha\rangle, \left|A\beta\right\rangle \ldots \left|omega\right\rangle\}$ where $|A\alpha\rangle$ through $|A\omega\rangle$ are any superpositions of vectors from $\{|A1\rangle, |A3\rangle, |A4\rangle, |A6\rangle \ldots |An\rangle\}$. Further, without loss of generality, say that Wigner's result is $\left|A\beta\right\rangle = \sqrt{\frac{1}{2}}(|A1\rangle + |A4\rangle)$. In this case we might think that Alice's result is at least a *partial* cause of Wigner's. Now I do not wish to enter into a discussion about partial causation here – it is far too far afield for our task.[42] However, note that our intuition is somewhat 'messy'. Given Wigner's result, it is certainly true that Alice must have observed either $|1\rangle$ or $|4\rangle$ in her perspective. But neither of these will lead to Wigner's result with certainty (as both must also appear in other basis vectors of Wigner's measurement). I would suggest that the intuition we have here is being pulled by the fact that Alice's outcome somehow *constrains* Wigner's possible outcomes. This may not be enough to posit a full causal relationship between the two outcomes, but allows us to say that Alice's outcome causes Wigner to observe one of a *subset* of possible outcomes – much like in the case above where we described a causal connection between Alice not observing $|0\rangle$ and Wigner not observing $|A0\rangle$.

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[41] Note that what we would need to answer this question is empirical evidence about what happens to a macroscopic system when it is measured in such a basis. We might attempt to theorize about such cases, but at the end of the day we have no reason to believe one possible description of Alice's experience over any other.

[42] See Paul and Hall [53] for some discussion of this, especially chp. 3.

Putting this together then, we see that this model allows for us to relatively easily arrive at the causal claims we want. It may be true that the possible world similarity relationship described results in some possibly counterintuitive claims about the relative closeness of certain worlds, but we can put this concern aside insofar as we aim only to describe the closest possible worlds for the sake of evaluating relevant counterfactuals. Moreover, as indicated at the start of this discussion, there are almost certainly alternative similarity relations that could be developed (and defended).

There remains one concern to address – the 'elephant that might have been in the room', perhaps: There is well-established, and well-justified concern that arises when discussing counterfactual conditionals in the context of quantum mechanics. Having laid out the theory, as well as a model of how it might work, it is worth reassuring ourselves that we haven't inadvertently suggested an approach that relies on claims that are known to be problematic.

3.6.5 Avoiding counterfactual concerns

Throughout my discussion here I've made no reference to any concerns that might be raised against using counterfactual reasoning in the quantum context. However, as demonstrated by Stairs [72], there is good reason to worry about this. As such, I wish to explicitly differentiate my use of counterfactuals here from those circumstances in which they are problematic.

Stairs is primarily concerned with claims about the outcomes of counterfactual measurements (where the claim's truth is evaluated based on actual measurement outcomes). For example, he raises the following case: say Andrea and Bob share a pair of particles in the singlet state. Andrea measures her qubit in the computational basis and observes $|0\rangle$. She is clearly in the position to assert the (indicative) conditional, "if Bob measures his qubit in the computational basis then he will observe $|1\rangle$." She can also assert, not knowing whether Bob has measured or not, that "if Bob measured his qubit in the computational basis then he observed $|1\rangle$".[43] However, Andrea cannot say that, "*had* Bob measured his qubit in the computational basis *he would* have observed $|1\rangle$," assuming that Bob hasn't measured his particle (or that he's measured it in another basis).

I have not yet addressed any cases of entangled particles – these will be discussed after considering invasive measurements in §5.1 below – but entanglement is not required to identify problematic counterfactuals in the quantum context. Going back to our case of Alice and Wigner, say Alice measures her particle in the $\{|+\rangle, |-\rangle\}$ basis and Wigner then measures Alice in the $\{|A0\rangle, |A1\rangle\}$ basis. It is immediately obvious that if Wigner obtains the result $|A0\rangle$ he cannot assert that, "had Alice measured in the computational basis she would have observed $|0\rangle$." Indeed, the same result is available without considering encapsulated measurements. If Alice has a qubit in some arbitrary spin state $|\theta+\rangle$, measures it in the computational basis, and then measures it in the $\{|+\rangle, |-\rangle\}$ basis to observe $|+\rangle$, we know that she cannot say "had I measured in the +/- basis to begin with I would

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[43] This ignores potential confusions about time ordering of events if they are spacelike separated, of course. I will look more closely at these cases in §5.1.

have obtained $|+\rangle$."

One way we might diagnose these problematic counterfactuals in terms of the theory presented here is to say that they contradict the predictions of the best system. Quantum mechanics tells us that the probability of obtaining a $|+\rangle$ when measuring a qubit in the state $|\theta+\rangle$ is $|\langle+|\theta+\rangle|^2$, which is not unity unless $|\theta+\rangle = |+\rangle$. Alice's later measurement results simply have no impact on the Born probabilities prior to the measurement. (Indeed, denying this would quickly lead the theorist into a local hidden variable theory.) Note that this applies to Stairs' cases as well. When Andrea and Bob share the singlet state, the Born rule dictates that spin measurement results are equiprobable. If Andrea measures her qubit, she might make predictions about Bob's qubit given her result, but this doesn't change the Born probabilities prior to her measurement.

Accepting such counterfactuals as problematic, we now see why those considered here are entirely innocuous: The causal claims we've examined don't require appealing to counterfactual measurements. More to the point, when Wigner considers what would have occurred in the event that Alice obtains a result other than what she obtains, he is not suggesting any violations of the best system at all - he is considering the law-like evolution of Alice's lab and some other nomologically possible measurement outcome. More specifically, neither antecedent nor consequent of the counterfactual presents a contradiction with what the best system dictates in Wigner's perspective. We therefore quickly see why Stairs' concerns, although legitimate, don't impact the discussion here.

3.7 Conclusion

To close our discussion on non-invasive measurements, I wish to respond to a point that has been raised in personal conversation, most recently by James Ladyman. By turning to Humean supervenience and the Mill-Ramsey-Lewis account of laws, it may seem like the position I've described is a 'cop-out'. That is, there is a sense in which neo-Humeanism is an 'anything-goes' system. The laws are not grounded in ontology. They offer no true constraint on what is actually possible. And they don't offer any satisfying explanation for the discrepancy between the quantum mechanics description of the world and the world we experience.

To this particular complaint I offer a simple response. First, my aim here is not to present and defend a unique perspectival theory. Rather, I wish to demonstrate that there does exist a philosophical foundation upon which a theorist may build a perspectival theory that avoids any metaphysically bizarre or counterintuitive conclusions while taking quantum mechanics to be both correct and complete. That is, I wish to show that quantum mechanics does not force us to accept many worlds, 'ψ-ontology', preferred inertial frames, or superluminal action. It also doesn't, on its own, prove to be inconsistent or inadequate. It is a theory that can be accepted *in toto* by rejecting certain intuitions about how physics *works*.

To this end it is worth going over how much of the above is actually demanded of the perspectivalist. Although I don't demand neo-Humeanism of the perspectivalist, I take the success of the Lewisian approach to reflect something about the structural requirements of perspectivalism. For example, we can start with one point that is entirely transparent, which is that the perspectivalist must take laws of nature as including some indexicalization. Whether or not the theorist adopts the Mills-Ramsey-Lewis theory, the fundamental laws can only describe physical evolutions from a single perspective at a time. Of course, this isn't very surprising given our central tenets.

If we then look specifically to the best system + mosaic structure, we can learn what the perspectivalist must say about her ontology given this indexicalization of the laws of nature (and specifically, the laws of quantum mechanics). As we saw, the indexicalization of the best system combined with the central tenets of perspectivalism limits the possible forms an ontology might take. Importantly though, the constraints we find here don't originate from any particular assumptions or results of Humean supervenience. In fact, it is perhaps *because* of the freedom to consider the laws of nature independently from ontology – a freedom that might be uniquely afforded by Humean or neo-Humean causation and Lewisian metaphysics – that the approach was so well-suited for our purposes. It permitted us to build a possible ontology that wasn't overly constrained by a theory that we explicitly rejected as representational from early on. The result, however, is somewhat surprising. It tells us the if quantum mechanics is correct and compete, albeit perspectival and probabilistic, then the underlying ontology is closer to a classical state space than we might have thought despite the fact that its dynamics are quantum mechanical.

In fact, you'll recall that I ruled out a classical ontology almost immediately by noting that position eigenstates are unphysical according to quantum mechanics. Looking back though, we now see that this might have been too quick. Our end result was a quasi-classical state space – states that were classical but for the fact that they were slightly spread out in phase space. However, even here we had to divorce our kinematics from our physical dynamics to avoid instrumentalism and representationalism. But once such a divorce is introduced into her metaphysics, the perspectivalist may return to the classical ontology if her theory calls for it. What she must accept in either case is that there is this divide between the underlying ontological state and the language of how systems evolve.

In a sense, this isn't surprising at all. If quantum mechanics is correct and complete but not representational then why should we expect the classical links between kinematics and dynamics to hold? Of course, this is a completely exotic notion in physics, but so is taking a fundamental theory to be non-representational! I take this point to be a foundational metaphysical position of the perspectivalist. It is this that permits her to describe a universe in which systems' interactions are governed by laws that must be applied from a perspective, as it is this that allows for descriptions of systems' states to diverge without giving up on a single, unique, and objective state of the universe.

Chapter 4: Invasive measurements

Having established the perspectivalist's position on non-invasive measurements, we now turn to the case of invasive ones. Recall that these cases are defined as those in which Wigner's measurement does not contain a basis vector that corresponds to Alice having observed her result. Again, in these cases we find another possible source of inconsistency. A standard, somewhat naive treatment of the scenario goes as follows: Alice will measure her qubit in the computational basis and Wigner will measure Alice in the $\{|A+\rangle, |A-\rangle\}$ basis.[1] Say Alice observes the result $|0\rangle$. She then reasons that she must be in the state $|A0\rangle$, and so the Born rule tells her that each of Wigner's possible outcomes are equiprobable. On the other hand, Wigner describes Alice as evolving unitarily to the state $|A+\rangle$, and so he predicts that he has a 100% chance of obtaining $|A+\rangle$ and a 0% chance of obtaining $|A-\rangle$.

This account, or one very similar to it, is considered by Baumann *et al*. [91] and revisited in Baumann and Wolf [27], for example. The later of these in particular aims to demonstrate the empirical difference between two types of quantum theories, specifically those that treat Alice's measurement as objectively (or as we

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[1] Recall these are defined as $|A\pm\rangle = \sqrt{\frac{1}{2}}\, |A0\rangle \pm |A1\rangle$.

might say now, 'perspective-independently') 'collapsing' her quantum state and those which maintain the universality of unitary evolution. As is probably obvious, those which treat her measurement as a perspective-independent change to her state will predict Wigner's measurement results to be equiprobable while those which deny this (for example Everettian mechanics), will agree that one of Wigner's possible outcomes is certain while the other has probability 0.

I mention Baumann and Wolf's result for two reasons, in fact. The first is that they present a carefully constructed version of the argument against the perspectivalist that must be addressed. As mentioned in §1.2, they explain that trouble arises if a theory permits a *scientific contradiction* – the existence of contradicting pieces of classical information at a single spatiotemporal location. Such a contradiction seems possible in the case of perspectivalism (which would be a 'subjective collapse model', as they describe the term) given the possibility for Alice to send Wigner classical information while maintaining coherency in her lab's state. The protocol here is somewhat standard: Say that her lab is entirely isolated but for a one-way communication channel. Alice can use this channel to send Wigner a prediction about how probable it is that he will measure, say $|A+\rangle$ given her outcome. Assuming that Alice correctly describes herself to be in the state $|A0\rangle$ or $|A1\rangle$ (depending on her outcome), this prediction can be sent while maintaining the coherence of her state as both of her possible results lead to a 50% chance of Wigner obtaining $|A+\rangle$. Formally, we can see this by looking to the evolution of the initial state of the qubit (q), Alice and her environment (a), and a system that will carry her prediction (p) as:

$$\begin{aligned} &|+\rangle_q \left|ready\right\rangle_a \left|ready\right\rangle_p \\ &\quad\rightarrow |0\rangle_q |A0\rangle_a |\text{‘50\%’}\rangle_p + |1\rangle_q |A1\rangle_a |\text{‘50\%’}\rangle_p \\ &\quad= \left(|0\rangle_q |A0\rangle_a + |1\rangle_q |A1\rangle_a\, a\right) \otimes |\text{‘50\%’}\rangle_p \end{aligned}$$

As this is a product state Alice may remain in a coherent superposition after sending Wigner her ‘50%’ prediction. However, this means that it is possible for Wigner to be in possession of conflicting predictions, forming the scientific contradiction.[2] We, therefore, have at least one test again which we can compare the final perspectivalist’s position.

The second reason is that Baumann and Wolf’s unusually detailed treatment of the argument is helpful in describing what, precisely, the perspectivalist must deny. More to the point, this paper, as well as the Frauchiger and Renner argument and Lazarovici and Hubert’s Bohmian response to them, offers a clear path forward for the perspectivalist emerges. This is to deny that Alice should make predictions about Wigner as if she is in any quantum state at all.

In what follows I will briefly go over the relevant part of Baumann and Wolf’s paper. This will be followed by a short summary of Frauchiger and Renner’s argument, which I have referred to but have not yet described. It is

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[2] This protocol is not discussed in detail in [27] but was given by Baumann when she presented the paper at *New Directions in the Foundations of Physics, 2019*. I do not wish to delve into the discussion surrounding this protocol and what it does or does not imply beyond what Baumann and Wolf consider. That said, it is worth noting that some have argued the entire protocol is unphysical, including for example Alexei Grinbaum [92].

necessary to do so, in particular to discuss Lazarovici and Hubert's response, which explains that it is incorrect for Alice to predict Wigner's outcome as if she is in the state $|A0\rangle$. Adopting a similar position, the perspectivalist is able to explain why Baumann and Wolf's argument fails and scientific is avoided.

Of course, identifying and adopting this Bohmian conclusion is not nearly sufficient for our purposes. We must also consider what justifies the claim that Alice cannot make such predictions. To do so I will first look at a theorem by Breuer [93] that proves that a measuring device cannot be included as a subsystem in the system it is measuring. Noting some weakness in the applicability of the theorem to our scenario, I will then offer a physically-motivated proof that Alice cannot measure herself, and moreover that she cannot have physical (nor, therefore, epistemic) access to how Wigner will describe her quantum state.

4.1 Baumann and Wolf

Baumann and Wolf demonstrate the empirical (or predictive) distinguishability of two quantum "formalisms," *standard quantum mechanics* and the *relative state formalism*. (Formalism are differentiated from quantum "interpretations" in that differences in the prior, but not the later, have empirical consequences.) The relative state formalism includes, for example, Everettian mechanics, which denies that unitary ever breaks in Alice's measurement. Only the prior is relevant to our purposes, however. In standard quantum mechanics,

> the description of a measurement is governed by two expressions.

> The *Born rule* gives the probability of a measurement result for a quantum state $|\phi\rangle$ and an observable $A = \sum_a a\, |a\rangle\langle a|$,
>
> $$p_\phi(a) = Tr\left(|a\rangle\langle a|\ |\phi\rangle\langle\phi|\right) = |\,\langle a|\phi\rangle\,|^2$$
>
> The *measurement-update rule* gives the quantum state of the system after the measurement,
>
> $$|\psi\rangle \xrightarrow[\text{result: a}]{A} |a\rangle$$
>
> . . . In particular, the measurement-update rule can be regarded as necessary for giving the correct probabilities for the results of consecutive measurements on one quantum system.

Of course, in the standard quantum mechanical formalism it is the measurement update rule (as applied to Alice's lab in our scenario) that results in the prediction that Wigner's +/- measurement outcomes are equiprobable. As they explain it, in the context of an encapsulated measurement, standard quantum mechanics implies that the observer and superobserver disagree about whether the measurement update rule is applicable after the observer's measurement. It is this that leads to a discrepancy in the predictions made about the superobserver's measurement as described.

Now the perspectivalist wishes to block this conclusion and it seems that she has very few options available. First, she may deny that Alice and Wigner can carry out the protocol that leads to scientific contradiction. This may be possible, but I will not pursue this line here, both because it would be quite difficult and because it is unclear whether it would be generally applicable.[3] Second, she may try to explain why Wigner's prediction is incorrect. However, any approach that results in denying Wigner's application of the Born rule to Alice's unitarily evolved state must fundamentally deny the central claims of the perspectival approach. That is, if no decoherence 'leaks' into (or out from) Alice's lab then the Born rule must provide the correct predictions in Wigner's perspective. Third, she may explain that it is Alice's prediction that is incorrect. This approach, which I will pursue here, is not at all in conflict with the perspectivalist position. In fact, there is a very natural reason to think that this approach is a good direction for the perspectivalist. We have spoken of perspectives as involving a quantum system and a classical system that measures it. But in the case at hand we're not asking Alice to predict the result of measuring another system, but rather to predict the result of another system measuring *her*. There is already something problematic about this – according to the central tenets of perspectivalism, Alice should be treating *Wigner* as evolving according to the Schrödinger equation, and not the other way around. Of course, we need a justification for blocking Alice's prediction, and for this we begin by turning to Frauchiger and Renner's recent paper as Lazarovici and Hubert's reply to them explains how such a move might work.

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[3] See footnote 2.

4.2 Frauchiger and Renner[4]

Frauchiger and Renner's goal is to prove that no physical theory can simultaneously satisfy three conditions. The first condition, ***Q***, amounts to the universality of unitarity combined with the Born rule probabilities for outcomes of measurement. It states that any observer can use quantum mechanics to predict the outcomes of measurements on any system, and specifically, that an agent can be certain of something that is predicted with probability 1. The second condition, ***C*** is a consistency condition that amounts to what might be called the transitivity of certainty. It states that if an agent A uses some theory to be certain than another agent B is certain of x (using the same theory that A uses), then A can be certain of x. Finally, condition ***S*** is a 'single world' condition, which states that if an agent is certain that x is true, then the agent must deny a negation of x.

To argue this, they present a thought experiment that might be seen as a combination of the Wigner's friend thought experiment [3] and Hardy's paradox [94], but which focuses primarily on the inferences that can be made by the agents involved. I will present the argument here with minor adjustments for clarity.

The experiment consists of two friends, Alice and Bob (each in an isolated lab) and two superobserving 'Wigners' who I will call Wigner$_A$ and Wigner$_B$. To begin, Alice 'tosses' a biased quantum coin in the state $\sqrt{1/3}\,|h\rangle + \sqrt{2/3}\,|t\rangle$ (where $|h\rangle$ and $|t\rangle$ represent heads and tails states, respectively). If the result of this toss is heads, she sends Bob a qubit in the state $|0\rangle$. If the result is tails, she sends Bob

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[4] §4.2 to §4.2.1 and part of §4.3.1.1 are adapted from [49].

a qubit in the state $|+\rangle$. Bob then measures his qubit in the computational basis. Once this is completed, Wigner$_A$ and Wigner$_B$ measure Alice's and Bob's labs, respectively, in the following bases:

Wigner$_A$	Wigner$_B$
$\|ok_A\rangle = \sqrt{\frac{1}{2}}(\|Ah\rangle - \|At\rangle)$	$\|ok_B\rangle = \sqrt{\frac{1}{2}}(\|B0\rangle - \|B1\rangle)$
$\|fail_A\rangle = \sqrt{\frac{1}{2}}(\|Ah\rangle + \|At\rangle)$	$\|fail_B\rangle = \sqrt{\frac{1}{2}}(\|B0\rangle + \|B1\rangle)$

Where $|Ah\rangle$ and $|At\rangle$ are the states of Alice having observed $|h\rangle$ and $|t\rangle$, and $|B0\rangle$ and $|B1\rangle$ are the states of Bob having observed $|0\rangle$ and $|1\rangle$.

Frauchiger and Renner then reason as follows: The combined Alice+Bob system can be described both as

$$\sqrt{\frac{2}{3}}\left|fail_A\right\rangle|B0\rangle + \sqrt{\frac{1}{3}}|At\rangle|B1\rangle \tag{4.1}$$

or as

$$\sqrt{\frac{1}{3}}|Ah\rangle|B0\rangle + \sqrt{\frac{2}{3}}|At\rangle\left|fail_B\right\rangle \tag{4.2}$$

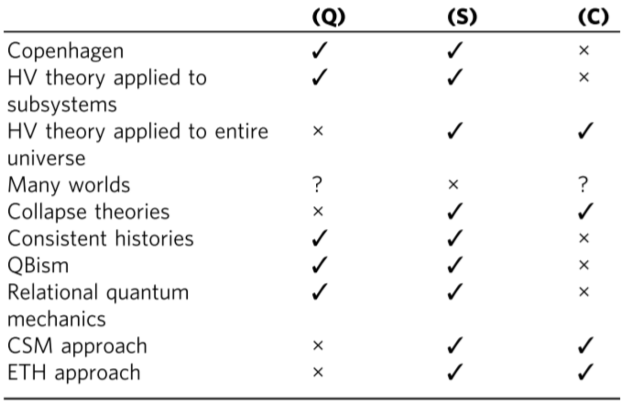
If Alice and Bob know that the Wigners will treat them as being in these states, and the Wigners know that Alice and Bob know this, then there is a chain of inferences that can be built using ***Q***, ***C*** and ***S*** that seems problematic:

- If Alice's coin toss results in $|t\rangle$. Alice can then infer (or 'be certain') from (2) that Wigner$_B$'s measurement will result in $\left|fail_B\right\rangle$ (using $\boldsymbol{Q}$).
- If Bob then measures $|1\rangle$, he can infer that Alice must have measured $|t\rangle$, as otherwise he would have been certain to measure $|0\rangle$. He can then reason (using $\boldsymbol{Q}$) that Alice can be certain (using $\boldsymbol{Q}$) that Wigner$_B$ will measure $\left|fail_B\right\rangle$, and so he can be certain (by $\boldsymbol{C}$) that Wigner$_B$ will measure $\left|fail_B\right\rangle$.
- If Wigner$_A$ then measures $|ok_A\rangle$, he can reason from (1) that Bob must have observed $|1\rangle$, which in turn means that he can be certain (using $\boldsymbol{Q}$) that Bob is certain (using $\boldsymbol{Q}$) that Wigner$_B$'s measurement will result in $\left|fail_B\right\rangle$. Thus, he too can be certain that Wigner$_B$ will measure $\left|fail_B\right\rangle$ (again, by (using $\boldsymbol{C}$).
- Finally, if Wigner$_A$ tells Wigner$_B$ of his result, then Wigner$_B$ can also be certain that he will measure $\left|fail_B\right\rangle$ (using $\boldsymbol{Q}$ and $\boldsymbol{C}$).
- However, according to the Born rule, ($\boldsymbol{Q}$) there is a non-zero probability of Wigner$_B$ observing $|ok_B\rangle$. Should this happen, Wigner$_B$ would then 'be certain' both that his measurement results in $|ok_B\rangle$ and in $\left|fail_B\right\rangle$, violating $\boldsymbol{S}$.

Frauchiger and Renner conclude, therefore, that no theory can consistently maintain $\boldsymbol{Q}$, $\boldsymbol{C}$, and $\boldsymbol{S}$.

4.2.0.1 What is ruled out?

Having described their thought experiment, Frauchiger and Renner proceed to discuss its implications for standard theories of quantum mechanics, arguing that each one violates at least one of $\boldsymbol{Q}$, $\boldsymbol{C}$, or $\boldsymbol{S}$. (See TABLE 4.1.)



	(Q)	(S)	(C)
Copenhagen	✓	✓	×
HV theory applied to subsystems	✓	✓	×
HV theory applied to entire universe	×	✓	✓
Many worlds	?	×	?
Collapse theories	×	✓	✓
Consistent histories	✓	✓	×
QBism	✓	✓	×
Relational quantum mechanics	✓	✓	×
CSM approach	×	✓	✓
ETH approach	×	✓	✓

Table 4.1: A table summarizing how standard theories violate one of the Frauchiger and Renner's assumptions. From [2, p.8].

Of the theories considered, many will clearly (and happily) violate one of the three conditions. For example, Everettian mechanics necessarily violates ***S*** (assuming that we identify agents across branches). Similarly, GRW-style collapse models will violated ***Q*** insofar as they add collapse dynamics to account for single outcomes. Putting these theories aside then, as Pusey notes, "the new threat is to interpretations that try to have their cake and eat it: an exact Schrödinger equation and objective, single measurement outcomes." [95, p.978].

In response to this threat, there has been a flurry of responses that have appeared in print and online. Most of these responses can be divided into two categories. First, there are responses that aim to adapt or extend well-formalized theories in order to avoid the problem. These include Copenhagen-style approaches that make claims about what Alice and Bob experience through the process, such as the responses of Salom [26] and Drezet [42] discussed in §2.2.2.[5] Second, there are those that defend existing, well-formalized positions against

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[5] As mentioned in 2.2.2, Drezet is mainly concerned with the Bohmian response but offer the Copenhagen-style response as well.

the challenge. These largely include responses from Bohmian theorists, and in particular Lazarovici and Hubert's response that I wish to focus on next.

4.2.1 Lazarovici and Hubert's response

Frauchiger and Renner, following Dürr, Goldstein and Zhangí [96], note that Bohmian mechanics requires applying the equations of motion to the universe as a whole (and not to its subsystems). But as Lazarovici and Hubert explain, it is this point that blocks the Frauchiger-Renner argument. The fact that Wigner's measurement can 're-cohere' the branches of the wave function that represent all of Alice's or Bob's possible outcomes means that the 'empty' parts of the wave function – those parts corresponding to outcomes Alice and Bob didn't observe – cannot be neglected when making predictions about the Wigners' measurements. Thus, even after measuring $|t\rangle$, Alice cannot neglect the part of the wave function corresponding to the possibility of her observing $|h\rangle$ to predict Wigner's measurement.

Frauchiger and Renner argue that this amounts to a violation of $\boldsymbol{Q}$, but as Lazarovici and Hubert explain, they do not deny that Alice and Bob can use the Born rule to predict outcomes of measurement. Rather, they argue that Frauchiger and Renner aren't using applying the theory correctly when considering Alice's predictions. Thus, "all three assumptions $\boldsymbol{C}$, $\boldsymbol{S}$ and $\boldsymbol{Q}$, if properly applied, hold true in Bohmian mechanics. In particular, by [considering the theory as applied to the universe as a whole], none of the experimentalists needs to come to the conclusion that assumption $\boldsymbol{Q}$ is violated. They will rather come to a – correct – conclusion about what the right quantum states are to which assumption $\boldsymbol{Q}$ refers.” [24, p.7][6]

I raise their argument because this disagreement highlights a hidden assumption in Frauchiger and Renner’s argument. To say that Bohmian mechanics requires a violation of $\boldsymbol{Q}$ as they claim, they must assume that Alice and Bob are correct to make predictions by assuming that their measurement results indicate their quantum states. Specifically, this assumption amounts to the inverse of their assumption $\boldsymbol{Q}$. Their $\boldsymbol{Q}$ can be paraphrased for our purposes as follows:

If an agent knows

- *that a system is in the state* $|\psi\rangle$ *at time* $t < t_0$,
- *that at time* t_0 *an observable of the system* M *with possible results* m_i *will be measured in a basis mathcalM* $= \{|m_1\rangle, |m_2\rangle, \ldots, |m_n\rangle\}$
- *and for a particular* $|m_j\rangle$, $|\langle m_j|\psi\rangle|^2 = 1$

then the agent can be certain that at the end of the measurement, the value of M *will be* m_j.

The hidden assumption, which I will call $\boldsymbol{Q'}$, can then be described as follows:

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[6] Lazarovici and Hubert correctly generalize their result, concluding that “the quantum theories that are actually embarrassed by the [Frauchiger and Renner] thought experiment are those claiming that the wave function or quantum state represents, in some sense, the epistemic state of an observer, that it is defined in terms of someone’s knowledge or information or belief.” It is perhaps worth explicitly stating that a perspectival theory will fall into this description of ‘embarassed’ theories. That is, what is required to mount the Lazarovici and Hubert defense is a reason for the ‘empty’ parts of the wave function to be, in their words, “causally efficacious” [24, p.5]. Such a claim may be tenable on its own in a perspectival theory, but certainly doesn’t come automatically - the theorist has much to do before she may leverage their defense.

If an agent knows that the value of a property M of a system S is m_j, *then the agent can be certain that the system is in a state* $|\psi\rangle$ *such that* $|\langle m_j|\psi\rangle|^2 = 1$.

Where ***Q*** says than an agent assigning probability 1 to some measurement outcome entails that the agent is certain of the outcome, ***Q′*** says that if an agent is certain of some outcome, she must describe the system as being in a state that predicts that outcome with probability 1.

We can see how ***Q′*** works by considering non-invasive measurements again. If Alice flips her quantum coin and obtains $|t\rangle$, then by the reasoning we've already seen she can be sure that if Wigner were to measure her in the basis $\{|At\rangle, |Ah\rangle\}$ he would obtain the result $|At\rangle$. As a result, she must describe herself to be in the state $|At\rangle$.

I will not provide a possible defense of the ***Q′*** assumption here – my purpose is not to argue against the Bohmian position of Lazarovici and Hubert's response. Rather, my point is that their response offers a direction for the perspectivalist too, as denying this assumption is essentially to deny the applicability of Baumann and Wolf's measurement update rule to Alice's state in her own perspective. Thus, what we need is a reason to deny ***Q′*** without relying on a Bohmian-style wave function realism.

4.3 Knowing one's state

In order to ground the perspectivalist's denial of ***Q′*** I will argue for a relatively simple, yet foundational claim: it is impossible for a system to describe its own quantum state. To show this, we will begin with a brief overview of Breuer's 1995 result concerning self-measurement. As I will explain, Breuer's proof will need to be slightly generalized for our purposes, which can be done by considering standard quantum results (and in particular the no-cloning theorem).

4.3.1 Breuer and "The impossibility of self-measurement"

Breuer's [93] (and again in [97]) presents a theory- and interpretation-neutral, logical proof that precludes the possibility for any measuring system M to accurately measure the state of a system S in which M is strictly contained. I will offer a brief overview of his argument here, though it is worth first mentioning that it will have two shortcomings. The first is the constraint just mentioned - that M be strictly contained in S. Although this makes good sense in any practical measurement context, it is not clear that this is enough for our purposes. The second is that it isn't obvious that the impossibility of *measuring* one's state translates to physical (or at least epistemic) *unavailability* of one's state, which is what really we need to deny $\boldsymbol{Q'}$. Despite these weaknesses though, the argument offers some insight into the types of considerations the perspectivalist can use to arrive at this conclusion.

Breuer's proof relies on two assumptions and one definition: *proper inclusion*, a *meshing condition*, and *exact measurability*. Proper inclusion relates to M's being strictly contained in S, and states that given this constraint it must be the case that S has more degrees of freedom than M. As such, there must exist distinct states of S, s and s' for which the state of M is identically m. The meshing condition is simply a condition of successful measurement. It states that the state s of S after measurement must be self-referential – the state of the subsystem M, m_s must refer to s. Finally, a state s_0 of S is defined to be exactly measurable if the final state of M, m_f refers to s_0 and only to s_0. That is, it is not the case that there exist multiple $s_0, s_1, \ldots$ that will all produce m_f.

Breuer then proves that given proper inclusion and the meshing condition, there exist states of S which are not exactly measurable. (What I present here is a simplified version of the argument. As I will not argue against Breuer's result, I don't see the need to reproduce it in full detail here.) By proper inclusion, take s_0 and s_1 to be distinct states of S for which the state of M is identically m. Following Breuer, let θ be a map from states of M to states of S. It should be understood as an "inference map", describing what can be inferred about the state of S given the state of M. Now, as Breuer notes, his "self-reference problems only occur if an observer wants to know his *present* state" [93, p.207] as this implies that the initial state of S – the state to be measured – and the final state of S must be contemporaneous (and hence identical). In turn, this means that we can apply the meshing condition to these initial states, which gives that it must be the case that $s_0 \in \theta(m)$. But by the same token it must also the case that $s_1 \in \theta(m)$. Therefore, the measurement cannot distinguish between s_0 and s_1. Given that the two states are indistinguishable, we have at least two states of S that M cannot measure.

4.3.1.1 Breuer's shortcomings

As mentioned above, there are two relevant shortcomings with Breuer's argument. The first is the constraint that M is strictly contained in S and the second is the possible distinction between self-measurement and self-description or self-knowledge.

The first of these turns out to be slightly difficult to discuss given what I've said so far. The reason for this is that I've tried to remain relatively non-committal about what constitutes an observer, let alone a perspective, and this is largely because I've tried to be careful about delineating precisely what the perspectivalist is and isn't committed to – I don't wish to impose unnecessary constraints on the view. That said, I will need to be somewhat more decisive and more careful now. It doesn't make sense to discuss whether a system can measure (or know) its own state without being clear about whether it can be an observer, let alone being clear about whether, for example, Alice's perspective is identical to the perspective of the collection of everything contained in her lab.

Despite being non-committal, I have maintained a preference for avoiding the introduction of metaphysical distinctions between the observer and the observed system without appropriate justification. (For example, I've argued against claiming that certain systems cannot act as an observing system or as having a perspective except in the case where our ontology suggested this may be the case.) I will now adopt this position more formally with a brief defense:

First, I do not see how the introduction of a distinction between systems that can and cannot act as observer could be defined non-circularly. I take it as given that all systems are composed of fundamental particles, so there is no purely compositional property that we could appeal to. One might try to look at a system's size or complexity, as mentioned earlier. However, as Schrödinger famously pointed out in [4], there is no principled cut off that might be introduced. Rather, this appeal seems to hide an intuition that larger systems experience single outcomes while smaller systems do not. But such a basis for the distinction is circular: we want to explain why some systems are be observers – *why* they experience single outcomes. We cannot appeal to the fact that they do to justify this.

There is another reason that we might want to avoid the introduction of such a distinction, which is that it seems to go against the universality of unitary evolution and forces a reevaluation of standard physical reductionism. To say that unitarity is universal is to say that it applies to all systems. But "system", as used in physics, denotes merely arbitrary collections of particles (or perhaps other physical objects, themselves composed of particles) which are merely contextually *salient*. It is not as if physics cares whether we describe two billiard balls as two systems, one system, or a collection of the order of 10^{24} systems. We could even describe a system composed of one billiard ball and one half of the second if we wish. However, to say that some systems experience single outcomes while others don't is to suggest that certain collections of particles experience very different physical evolutions than others. Not only does this imply that our physics is incomplete (as it doesn't offer multiple types of evolution) but it also presents a true hurdle for reductionism. If single particles don't experience single outcomes then the states of complex systems cannot supervene on the states of the particles that compose them. How can a billiard ball determinately go left or right if none of its particles do?

Of course, the perspectivalist has no reason to suggest that different physics applies at different scales, and moreover, it is a central tenet that unitary dynamics is universal. It is the *only* law of physical evolution, and so it must apply at all sizes and scales. By adhering to this and explicitly denying that there is some distinction between systems that can and systems that can't observe single outcomes, the perspectivalist can afford a flexibility in describing perspectives that will maximally generalize her position. That is, she can explain that Alice has a perspective, as does her environment, the lab as a whole, her measuring device, even her right arm.[7]

There is a very nice parallel that can be found in the theory of special relativity. Here the fine-graining of reference frames depends on the situation under consideration. For example, if calculating gravitational lensing observed from Earth, two human observers may be treated as being in the same reference frame. However, if closing the locality loophole in a Bell test, we may want to treat them as being in distinct frames. The perspectivalist may say something similar about perspectives given that she doesn't limit which systems may count as observers. In some cases, such as when Wigner measures Alice's lab, they

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[7] Just to be clear, we've seen that there may be a distinction (albeit a possibly vague one) that arises from the ontology, but this would be entirely explicable and well-justified.

represent different perspectives. However, if they are together measuring some other system, then the situation may justify a coarse graining that places them in a single perspective. (Although it may not be necessary, this could be defended by appealing to decoherence theory given the spatiotemporal proximity of their observations, for example.)

In other words, by avoiding such a distinction the perspectivalist ensures that she avoids the introduction of unjustifiably privileged perspectives. It ensures, for example, that unitary evolution is truly universal insofar as it can be correctly used to describe any collection of particles' interactions with any other collection of particles. Thus, Alice will describe the rest of her lab as a quantum system, Alice and her measuring device can treat the air in her lab as a quantum system, etc. (We can even speak of Alice's right hand treating her left one as a quantum system.) Even more, it ensures that any interaction between two systems should be describable from 'both sides'. Not only does Wigner treat Alice and her lab as a quantum system, but now we can explain that Alice and her lab treat Wigner as a quantum system as well. [8]

Given this flexible notion of what constitutes an observer we can turn to Breuer's argument. It is tempting to say that Breuer's proof can immediately rule out the possibility that Alice can adequately measure the state of the entire lab. However, this is slightly too quick. What can be ruled out is Alice using some measuring device that to measure the state of the entire lab. But this isn't

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[8] This is not a novel claim. It is somewhat formalized in work on quantum reference frames, for example [13], and Brukner has expressed agreement with it in personal conversation.

nearly enough to block $\boldsymbol{Q'}$ or a scientific contradiction. Consider the following: Imagine that instead of Alice and her lab we have an isolated device whose entire purpose is to measure its own state, including the computational basis spin of a qubit it contains. If we call this device 'AutoAlice' and replace it for Alice's lab in our original encapsulated measurement then nothing needs to change but for Alice's name (permitting some anthropomorphisation of the device, of course). My intent here is to demonstrate that Breuer's assumption is too strong for us. The perspectivalist must allow for the possibility that the measuring device *just is* its own measured system, in which case the proper inclusion assumption doesn't hold.

Now one way forward may be to show that AutoAlice is unphysical for some reason. That is, she may seek to ground Breuer's assumption as being necessarily true.[9] However, there is a more general path forward, which is to appeal to the nature of quantum measurement to demonstrate that no such device is generally describable given the laws of quantum mechanics.

Insofar as the measuring device is to succeed in actually *measuring* its own state, there must be some sort of record or signal created that is entirely dependent on the state of the entire system. Another way to frame this is to note that it is inadequate for the system to measure its state that it merely *be* in that state. There

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[9] I can see multiple ways such a proof may proceed. For example, it may be provable that in such a case we lose the distinction between a measurement and an encapsulated measurement, which could lead to inconsistencies given our central tenets. Alternatively, one might argue that for such a device to exist it would require infinite resources, for example because it would require some memory to record any bit of information about its state, and then more memory to record the physical state of the memory medium that recorded that bit, and so on. In any case, I will not pursue such an argument here.

must also be an encoding of the state analogous to Breuer's state of M.

Call this signal or record the system's *output*.[10] To maximize generality, we should avoid assumptions about the form of the output. For example, it should not be assumed that this output must be comprehensible to any other system, let alone a human observer. This can be motivated by noting that in the quantum context we could try to record the system's state in another quantum state (or collection of quantum states). Doing so may mean that the encoded state may be not retrievable (by Holevo's bound), but to maximize generality this would be considered an output for our purposes.

Let the portion of the device where the output is recorded be the subsystem O, and the remainder of the measuring device be the subsystem S.[11] We can then describe how the device must operate from some external perspective: The device must measure itself in some basis $\{|\alpha_i\rangle\}$ such that at the end of the measurement O must be in a state that reflects the measurement's result. Thus, we need the system to evolve under some evolution $U_{measurement}$ such that

$$|\alpha_j\rangle_{SO} \xrightarrow{U_{measurement}} |\alpha'_j\rangle_S \otimes |``\alpha''_j\rangle_O$$

where $|\alpha'_j\rangle_S$ is the state of S after the measurement.

This description gives us an initial constraint immediately: It mirrors the

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[10] This should not be understood as requiring that system send this record to any receiver.

[11] It might be thought that dividing the system like this just amounts admitting Breuer's proof, as now we can ask about whether O has as many degrees of freedom as S. This may well be an example of how one might argue that the system I'm describing is unphysical. However, I will ask us to put this concern aside for the sake of argument.

evolution which is precluded by the no-cloning theorem for a single unitary operator given a general state $\left|\alpha_j\right\rangle$ [98]. What this means is that we can immediately conclude that there cannot exist a device that measures itself in an arbitrary state using a single measurement process. This is simple enough to prove:

Assume the evolution is achieved by $U_{measurement}$ for states $|\alpha_j\rangle$ as described. For the system to measure itself in an arbitrary state, it should be that if the device were to begin in the state $\sum_i c_i |\alpha_i\rangle$, (for normalized constants c_i) then the final state of O should be $|``\sum_i c_i |\alpha_i\rangle"\rangle_O$. However, by the linearity of the Schrödinger equation, the state would evolve as

$$\sum_i c_i |\alpha_i\rangle_{SO} \xrightarrow{U_{measurement}} \sum_i (c_i |\alpha_i'\rangle_S \otimes |``\alpha_i''\rangle_O)$$

which is quite different from what is desired. According to our central tenets, the device will observe a single result of this measurement – one of the $|\alpha_i'\rangle_S \otimes |``\alpha_i''\rangle_O$ – rather than the initial state, as required.

We might try to add other possible unitary evolutions to the device, each of which achieves the desired evolution for a different basis. So perhaps the measurement device operates by evolving in one of the following

$$
\begin{aligned}
|\alpha_j\rangle_{SO} &\xrightarrow{U_\alpha} |\alpha'_j\rangle_S \otimes |``\alpha''_j\rangle_O \\
|\beta_j\rangle_{SO} &\xrightarrow{U_\beta} |\beta'_j\rangle_S \otimes |``\beta''_j\rangle_O \\
|\gamma_j\rangle_{SO} &\xrightarrow{U_\gamma} |\gamma'_j\rangle_S \otimes |``\gamma''_j\rangle_O \\
&\vdots
\end{aligned}
$$

for distinct operators U_α, U_β, and U_γ. But two further problems arise:

First, it is likely obvious that even if such a sequence of unitary evolutions were available to the measuring device, this would not help very much. In order for the device to know which measurement setting to use it would have to know ahead of time which basis to use, which is highly non-trivial if we assume that the system can be in any state prior to measurement.[12]

What is even worse, though, comes from considering that we want the measuring device output to reflect the state that it *is* in, not the state that it *was* in. Our goal, recall, is to figure out whether a system can make a prediction about what a superobserver will observe when measuring it. If measuring the state changes it then the output cannot be used to make sure a prediction. This perfectly parallels Breuer's note about the applicability of the meshing condition

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[12] This may seem trivial given the encapsulated measurement scenario we have been looking at so far, as it seems like Alice/AutoAlice knows ahead of time to measure in $\{|A0\rangle, |A1\rangle\}$. I will discuss this further in the following section, but for the moment note simply that this assumption is unfounded. Wigner doesn't describe her in as being in a state in this basis, and what we are questioning is whether Alice has reason to assume this. Unless we have an independent reason to think that she is already in this state, conducting a measurement in this basis would simply be begging the question.

to the final states of S in his proof.

What this means is that the state described in the output must also be the state of the entire device at the time of the output. If the output reads "ψ" then the state of the device after the measurement must be $|\psi\rangle_{SO}$. But given that the output should reflect the state of the machine prior to measurement, the initial state of the device must also be $|\psi\rangle_{SO}$. This means that U_α, U_β, $\ldots$ can only be identity operators. In other words, the device must begin in a state in which its output already reads "ψ" – it must already know its state before it measures it!

We can, therefore, begin to strengthen Breuer's theorem. In the quantum context, the measuring device need not be strictly contained in S but can also be identical to S for self-measurement to be precluded. This leaves the second shortcoming to deal with, which is whether this result is sufficient to block Alice's prediction.

4.3.2 The impossibility of self-*description*

The impossibility for AutoAlice to measure herself isn't quite enough to address the case of Alice and Wigner. A perspectival skeptic may respond by claiming that Alice (the human) is not at all like AutoAlice. In the encapsulated measurement scenario, Alice doesn't measure the state of the entire lab. Rather, she measures her qubit and learns from her result that the state of the lab must project onto the relevant Hilbert subspace that Wigner is concerned with.

Now the perspectivalist may respond to this concern quite easily. *Assuming* that Alice is correct to describe herself in either $|A0\rangle$ or $|A1\rangle$ completely begs the question. We already know from the work of Lazarovici and Hubert [24] (and Dürr, Goldstein and Zhangí [96]) that quantum mechanics precludes using this state to make predictions about measurements on Alice. Following them, the perspectivalist can explain that Alice can *know* that this method will not produce the quantum state relevant for Wigner's measurement as it would imply that Wigner's application of the unitary dynamics to Alice's lab is incorrect. Moreover, note that we have no other reason to think that Alice is in one of $|A0\rangle$ or $|A1\rangle$ at all. This comes entirely from an attempted application of the measurement update rule (or something like it), but even this is flawed. It is Alice's qubit, not Alice herself, that is measured, and so the rule doesn't say anything about the state of Alice. The assumption that she should describe herself as being in one of these states comes only with with assumption that she is in one of them to begin with.

Nonetheless, our job is not finished here. The skeptic may push back further: Recall that to arrive at a scientific contradiction, as Baumann and Wolf have described, there must be conflicting pieces of classical information at a single point in spacetime. What we have done so far is to explain that Alice cannot make a prediction about Wigner's outcome using her result, thereby permitting a scientific contradiction to appear outside the lab. However, this does not prevent the possibility of finding a scientific contraction from occurring *inside* the lab. Consider the following: Instead of attempting to measure or describe her lab's state given her measurement outcome, Alice instead calculates her unitarily evolved state from within the lab. She thereby describes her lab to be in, say $|A+\rangle$, which means that there is a 50% chance that if Wigner were to conduct a measurement in the $\{|A0\rangle, |A1\rangle\}$ basis he would find that she had observed $|1\rangle$. This contradicts her prediction about the non-invasive measurement considered in chapter 2.

To respond to this concern then, we must explain why Alice either should not, or cannot describe her entire unitarily evolved state. And in order to address this we must first be slightly more careful about how it is that Wigner arrives at his description of the lab's state.

Thusfar, we have used the following gloss on Wigner's description: The lab contains the qubit (q) and Alice (a), who we have treated as standing in for everything else in the lab. Wigner describes the lab as starting in the state $|+\rangle_q \otimes \left|ready\right\rangle_a$ (where q is the qubit and $\left|ready\right\rangle_a$ is some pre-measurement state of Alice and the rest of the lab) and evolving to the state $\sqrt{\frac{1}{2}}(|A0\rangle + |A1\rangle)$ where $|A0\rangle = |0\rangle_q \otimes |seen\,0\rangle_a$ and $|A1\rangle = |1\rangle_q \otimes |seen\,1\rangle_a$. This has been justifiable insofar as we haven't yet been concerned with the state of the lab outside of the Hilbert subspaces defined by the $\{|A0\rangle, |A1\rangle\}$ basis. But, of course, this is a tremendous oversimplification of the calculation that Wigner must do to project the final state onto the relevant subspace. Most importantly for our purposes now, it completely neglects the relative phase between the $|A0\rangle$ and $|A1\rangle$ branches of the state.

A more accurate description of the final state would be $\sqrt{\frac{1}{2}}(|A0\rangle + e^{i\theta}|A1\rangle)$, where θ is some angel between 0 and 2π. This relative phase angle can make all the difference, of course. For example, if $\theta = \pi$ then $e^{i\theta} = e^{i\pi} = -1$, bringing $\sqrt{\frac{1}{2}}(|A0\rangle + e^{i\theta}|A1\rangle)$ to $\sqrt{\frac{1}{2}}(|A0\rangle - |A1\rangle)$. In other words, if we consider Wigner's treatment of Alice's evolution more carefully, our earlier description of Wigner's predictions for the +/− measurement can be completely incorrect. A simple application of the Born rule shows us that the actual probability of a $|A+\rangle$ result can be anything between zero and one:

$$\begin{aligned}
\text{Probability of } |A+\rangle \text{ given } |A(\theta)\rangle = \sqrt{\frac{1}{2}}(|A0\rangle + e^{i\theta}\,|A1\rangle) \\
&= |\,\langle A+|A(\theta)\rangle\,|^2 \\
&= \frac{1}{4}(\langle A0| + \langle A1|)(|A0\rangle + e^{i\theta}\,|A1\rangle)(\langle A0| + e^{-i\theta}\,\langle A1|)(|A0\rangle + |A1\rangle) \\
&= \frac{1}{4}(\langle A0|A0\rangle + e^{i\theta}\,\langle A1|A1\rangle)(((\langle A0|A0\rangle + e^{-i\theta}\,\langle A1|A1\rangle) \\
&= \frac{1}{4}(1 + e^{i\theta})(1 + e^{-i\theta}) \\
&= \frac{1}{2}(1 + cos(\theta))
\end{aligned}$$

which, of course, varies from 0 to 1 with $0 < \theta < 2\pi$

Note that the appearance of relative phase differences is ubiquitous - I am not being nit-picky in raising it. They arise easily even in very simple systems. Take a free particle in a momentum eigenstate. In this case, momentum eigenstates and energy eigenstates are identical as

$$\hat{E}\Psi(p,t) = \hat{H}\Psi(p,t) = -\frac{\hbar^2\hat{p}^2}{2m}\Psi(p,t) = \frac{p^2}{2m}\Psi(p,t) = E\Psi(p,t)$$

Looking then to the time evolution of the particle in the energy basis, the time evolution operator U is generated by the Hamiltonian,

$$U\Psi(p,t) = e^{\frac{-iHt}{\hbar}}\Psi(p,t) = e^{\frac{-iEt}{\hbar}}\Psi(p,t)$$

This directly tells us that the time evolution of momentum eigenstate introduces a phase shift determined by the system's energy and time. If we then look to a system that begins in some superposition of momentum states $\left|p_1\right\rangle$ and $\left|p_2\right\rangle$ with energies $\frac{p_1^2}{2m} = E_1$ and $\frac{p_2^2}{2m} = E_2$, respectively, we get that

$$\begin{aligned} c_1 \left|p_1\right\rangle + c_2 \left|p_2\right\rangle &\xrightarrow{U} e^{\frac{-iE_1 t}{\hbar}} c_1 \left|p_1\right\rangle + e^{\frac{-iE_2 t}{\hbar}} c_2 \left|p_2\right\rangle \\ &= c_1 \left|p_1\right\rangle + e^{\frac{i(E1-E2)t}{\hbar}} c_2 \left|p_2\right\rangle \end{aligned}$$

which introduces a time-dependent relative phase angle of $(E_1 - E_2)^t/\hbar$.

This is all to show that the introduction of a non-trivial phase shift in the case of Alice's evolution is not at all farfetched. The highly complex Hamiltonian, as well as the high dimensionality of the lab's state space means that it's entirely possible for the $|+\rangle_q \otimes |ready\rangle_a$ state to evolve to a state where Wigner's measurement is more likely to result in $|A-\rangle$ than $|A+\rangle$.

Knowing this high sensitivity to the relative phase may make it even more difficult to imagine how Wigner could accurately describe Alice's evolution. More importantly, though, it also means that it is impossible for Alice to do so herself. Alice would have to know both the state of the lab prior to her entering it as well as how she will interact with this state at the quantum scale. But for her to know this she would have to know her exact state prior to this interaction. This quickly puts us into an infinite regress: Say Alice enters the lab at time t_0. Breuer's theorem and our further considerations have proven that Alice cannot measure her own state, so in order to calculate her lab's evolution she would have to have calculated her state at time $t_{-1} < t_0$ (to evolve until she enters the lab). But in order for her to do this she would have to have calculated her state at $t_{-2} < t_{-1}$, and so on. (Moreover, this neglects to account for the fact that Alice's state will presumably have decohered in the environment outside the lab. Taking this into account, Alice's calculation of her state at t_{-1} would, at best, produce a highly complicated mixed state at the time after her measurement. Taking this into account we would have to be very careful about how we determine whether or not a scientific contradiction even follows, as the probabilities produced by the density matrix blur the line between epistemic and Born probabilities.)

This consideration equally precludes the protocol described by Baumann and Brukner. As mentioned in §1.2, they consider the possibility of Wigner sending Alice information about her state. However, even if we permit that Wigner might convey to Alice her exact state, we must then consider that the introduction of any information into her lab corresponds to the introduction of some new physical system as well.[13] As such, Alice cannot describe the exact state of the lab after she receives this information without knowing the exact state of the lab and the system introduced prior to its arrival, which puts us into precisely the same position we just considered.

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[13] In fact, if Wigner is sending Alice her a relatively accurate description of her phase angle then her would have to send a relatively large number of bits.

4.4 Conclusion

Bringing this all together, the perspectivalist has a direct and simple means of avoiding inconsistency in the case of invasive measurements. Baumann and Wolf provide a clear description of the problem in terms of scientific contradictions. Taking direction from the Bohmian response to Frauchiger and Renner's argument, we find that we need to reject their implicit assumption $\boldsymbol{Q'}$. To do so, we explain that Alice cannot know, and has no reason to assume, that she is in $|A0\rangle$ or $|A1\rangle$ despite her measurement result – and despite the fact that she can predict Wigner's 0/1 measurement with certainty. But in addition to blocking $\boldsymbol{Q'}$ we also find that our reasoning further implies the inability for Alice to calculate her own unitarily evolved state. This blocks the possibility of a scientific contradiction appearing at any spatiotemporal point, be it inside or outside Alice's lab.

Importantly, nothing I have said here about the case of invasive measurements has contradicted anything about non-invasive measurements. It is not the case, for instance, that Alice makes a prediction about Wigner's non-invasive measurement by considering her quantum state. As mentioned, her prediction here is quite classical. Furthermore, recall that Alice might not know whether Wigner will make an invasive or non-invasive measurement. This isn't problematic insofar as Alice can say, after her measurement result, "if Wigner's measurement includes an eigenvector corresponding to my having observed the result I actually did, then this will be his result. If his measurement doesn't include this vector, then I have no prediction about what he will observe." I reinforce this only to once again highlight that the perspectivalist doesn't make any claim to the effect that these measurements evolve differently or observe different physics. All measurements are simply quantum interactions resulting in single outcomes as per the Born rule. The fact that encapsulated measurements involve measuring Alice doesn't change this fact.

Combining the results of Parts 2–4, we have seen that the perspectivalist is entirely equipped to avoid the contradictions that are typically brought up. This leaves one topic to address before we conclude.

Chapter 5: Conclusion (and entanglement too)

There are likely a number of questions that arise from what I have presented here, but one stands out so loudly that it would be negligent for me not to address it before I conclude. Quantum mechanics doesn't merely describe probabilistic (rather than deterministic) outcomes of measurement. It also describes how the states of interacting systems change such that we cannot describe the state of either system independently of the other. Coining this phenomenon as 'entanglement' Schrödinger explains that he "would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." [99, p.555] I must, therefore, explain what the perspectivalist has to say about this phenomenon. And it turns out that all we need for this follows from Parts 2 and 3.

5.1 Entanglement

The worry that entanglement raises for the perspectivalist is likely quite clear. Consider a pair of entangled electrons in a Bell state. The ontological picture that was drawn in §3.5 looks to demand that each of the electrons has a local state in the mosaic. If we assume that the Born probabilities are dependent on the ontic state, this implies either that quantum mechanics entails action at a distance or that quantum mechanics is incomplete. The latter is ruled out by assumption, and the prior is certainly something we would prefer to avoid. However, looking back to the discussion in §2.2.2, we can see that the worry is mitigated by the probabilism that we have adopted.

Recall that in our discussion of non-invasive measurements we turned to the perspective of a super-superobserver to see how consistency is maintained. In this perspective we considered the unitary evolution of Alice and Wigner together and noted that there were no terms of the form $|A0\rangle |W1\rangle$ or $|A1\rangle |W0\rangle$. The same strategy can be considered here:

Say that Andrea A and Bob B are in isolated, spacelike separated labs. They share a pair of photons, γ_A, γ_B in the singlet state. They also each hold an electrons, e_A and e_B, each in the $|+\rangle$ state. They will each measure their electron in the computational basis and their result will determine their measurement on their photon. If they measure $|0\rangle_{e_A/e_B}$ then they'll measure the polarization of their photon in the computational basis too, which I'll represent as a state of Alice/Bob as $|z\rangle_{A/B}$, and if they measure $|1\rangle_{e_A/e_B}$ they'll measure their photons in the $\{|+\rangle_\gamma, |-\rangle_\gamma\}$ basis, which I'll represent as states $|x\rangle_{A/B}$.[1] If we consider a 'third party' perspective who treats all systems as evolving unitarily, the evolution of

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[1] In case this isn't clear, the states $|z\rangle_A$, for example, should be read as "the state of Alice given that she will measure her photon in the computational basis". Similarly, $|x\rangle_B$ is the state of Bob given that he will measure in the +/- basis.

the electrons, photons, and Andrea and Bob will be:

$$
\begin{aligned}
&\sqrt{\frac{1}{2}}(|0\rangle + |1\rangle)_{e_A} \otimes \sqrt{\frac{1}{2}}(|0\rangle + |1\rangle)_{e_B} \otimes \left|ready\right\rangle_A \otimes \left|ready\right\rangle_B \otimes \sqrt{\frac{1}{2}}(|01\rangle - |10\rangle)_{\gamma_A,\gamma_B} \\
\rightarrow &\Big(\frac{1}{2}(|0\rangle_{e_A} |z\rangle_A |0\rangle_{e_b} |z\rangle_B) + \frac{1}{2}(|0\rangle_{e_A} |z\rangle_A |1\rangle_{e_b} |x\rangle_B) + \frac{1}{2}(|1\rangle_{e_A} |x\rangle_A |0\rangle_{e_b} |z\rangle_B) \\
&+\frac{1}{2}(|1\rangle_{e_A} |x\rangle_A |1\rangle_{e_b} |x\rangle_B)\Big) \otimes \sqrt{\frac{1}{2}}(|01\rangle - |10\rangle)_{\gamma_A,\gamma_B} \\
\rightarrow &\frac{1}{2\sqrt{2}}\Big[(|0\rangle_{e_A} |z\rangle_A |0\rangle_{e_b} |z\rangle_B |0\rangle_{\gamma_A} |1\rangle_{\gamma_B}) - (|0\rangle_{e_A} |z\rangle_A |0\rangle_{e_b} |z\rangle_B |1\rangle_{\gamma_A} |0\rangle_{\gamma_B}) \\
&+ (|1\rangle_{e_A} |x\rangle_A |1\rangle_{e_b} |x\rangle_B |+\rangle_{\gamma_A} |-\rangle_{\gamma_B}) - (|1\rangle_{e_A} |x\rangle_A |1\rangle_{e_b} |x\rangle_B |-\rangle_{\gamma_A} |+\rangle_{\gamma_B})\Big] \\
&+ \frac{1}{4}\Big[(|0\rangle_{e_A} |z\rangle_A |1\rangle_{e_b} |x\rangle_B |0\rangle_{\gamma_A} |+\rangle_{\gamma_B}) - (|0\rangle_{e_A} |z\rangle_A |1\rangle_{e_b} |x\rangle_B |0\rangle_{\gamma_A} |-\rangle_{\gamma_B}) \\
&- (|0\rangle_{e_A} |z\rangle_A |1\rangle_{e_b} |x\rangle_B |1\rangle_{\gamma_A} |+\rangle_{\gamma_B}) + (|0\rangle_{e_A} |z\rangle_A |1\rangle_{e_b} |x\rangle_B |1\rangle_{\gamma_A} |-\rangle_{\gamma_B}) \\
&+ (|1\rangle_{e_A} |x\rangle_A |0\rangle_{e_b} |z\rangle_B |+\rangle_{\gamma_A} |0\rangle_{\gamma_B}) - (|1\rangle_{e_A} |x\rangle_A |0\rangle_{e_b} |z\rangle_B |-\rangle_{\gamma_A} |0\rangle_{\gamma_B}) \\
&- (|1\rangle_{e_A} |x\rangle_A |0\rangle_{e_b} |z\rangle_B |+\rangle_{\gamma_A} |1\rangle_{\gamma_B}) - (|1\rangle_{e_A} |x\rangle_A |0\rangle_{e_b} |z\rangle_B |-\rangle_{\gamma_A} |1\rangle_{\gamma_B})\Big]
\end{aligned}
$$

It shouldn't be surprising that this entangled state doesn't include terms where Andrea and Bob measure their photons in the same direction and observe the same result. (I trust it is clear that if we were to consider a more general protocol that didn't force Andrea and Bob to select measurement bases from the same set then our results would provide the expected quantum correlations.) Thus, just as in the case of non-invasive measurements, we find that if we assume that all systems evolve unitarily in some external perspective then certain constraints are imposed on their combined evolution (which would not be expected under non-unitary evolution). Importantly, there is no action at a distance required here

– nothing *happens* when Alice measures her photon that changes Bob's state.

(Note that I have included e_A and e_B in this description only to explicitly reinforce that Andrea and Bob are quantum systems and so their measurement choices can be understood as branches in a unitary evolution. That is, we could eliminate the electrons from this and would arrive at the exact same conclusion provided we model Andrea and Bob as being in a superposition of measuring in the computational and +/- bases prior to measurement. Second, Andrea and Bob don't need to be in isolated labs *per se*, but if they are not then the third party perspective description will be far more complicated as it must include all systems that become entangled with each of them.)

Looking to this third-party perspective may seem entirely unsatisfactory. Unlike in the case of non-invasive measurements, there doesn't seem to be any causal claim we can intuitively justify in order to explain the correlated results (assuming we don't allow for action at a distance, that is). When we try to imagine how things appear from Andrea's perspective, for example, it looks as though her measurement *must* have a non-local effect on Bob's photon. (And it doesn't help to note that these correlations are maintained in a unitary treatment of Alice and Bob because we know that the result of the measurement could have been different.)

I want to argue now that the reason this feels inadequate is due to intuition about how the laws of physics operate. We take the explanations that physics offers to be available to all observers. That is, we don't think that certain observers have privileged access to certain explanations. For instance, if we consider two systems colliding, we expect that all observers will be able to explain how the collision occurs (along with what they observe) by appealing to the conservation of energy and momentum. In the quantum context this translates into an expectation that the explanatory power of the evolution observed in one perspective should be available to all perspectives – including those being described as evolving unitarily.

I will explain this further by looking to Wigner [100] and then show that the perspectivalist is already forced to reevaluate this intuition, at least to some degree, well before we consider the correlations of spacelike separated entangled systems. (This may not be surprising given our discussion in §3.4 but will offer some help into how the perspectivalist can better align her view with other physical theories.)

To say that it is an 'intuition' that physical explanation should be available to all observers is probably too weak. Insofar as physical explanation is fundamentally tied to nomological constraints imposed by the theory, this intuition it deeply tied into our scientific method. As Wigner explains in the opening of [100]

> The world is very complicated and it is clearly impossible for the human mind to understand it completely. It has therefore devised an artifice which permits the complicated nature of the world to be blamed on something which is called accidental and thus permits him to abstract a domain in which simple laws can be found. The complications are called initial conditions, the domain of regularities,

> laws of nature. Unnatural as such a division of the world's structure may appear from a very detached point of view, and probable though it is that the possibility of such a division has its own limits, the underlying abstraction is probably one of the most fruitful ones that human mind has made. It has made science possible. [100, p.521]

This intuition or assumption that our laws should be independent of 'accidental' facts amounts to the fundamentality of principles of invariance (and equivalently, conservation laws).[2] And, as is well known, particular instances of invariance principles have led to some of the largest theoretical advances in physics, most notably the development of the special and general theories of relativity.

I turn to Wigner's paper here because he offers an insightful and relevant description of the role of invariance principles in both classical and quantum physics:

> On the one hand, [invariance principles] give a necessary condition which all fundamental equations must satisfy: the irrelevant initial conditions must not enter in a relevant fashion into the results of the theory. Second, once the fundamental equations are given, the principles of invariance furnish, in the form of conservation laws and otherwise, powerful assistance toward their solution. [100, p.523]

What I wish to press from this is that if we take invariance principles as Wigner describes – as filtering out initial conditions from our laws and providing constraints

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[2] I am not distinguishing here between invariance and covariance. The different between these is not relevant for our purposes nor for those described by Wigner here.

on the solutions to our laws of motion – there is an immediate consequence for any perspectival account of natural laws:

The perspectival approach claims that quantum mechanics can only be applied from a single perspective at a time. If quantum mechanics is truly our fundamental physics then our principles of invariance can only be applied from a single perspective too. To put this in Wigner's terms, when it comes to quantum mechanics, the perspectivalist has claimed from the outset that at least one factor, namely the perspective from which the theory is applied, has been mistaken as accidental. In fact, this does influences "the results of the theory". In parallel, she can note that there are symmetries and conservation laws that do *not* hold when we neglect to consider the perspective from which the theory is applied. For example, I have demonstrated elsewhere [101] that the conservation of probability can be associated (via Noether's theorem) with the symmetry of global phase shifts. However, one perspective's global phase shift is another perspective's relative one.[3]

A direct consequence of the fact that invariance principles cannot generally be applied across perspectives is that we should not expect a physical explanation available in one perspective to be available in any other. This doesn't mean that this is not possible – when quantum systems are not isolated (so that they decohere continuously into their environments), macroscopic systems do not notice the perspectival dependence of their physics and we find all the standard invariances

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[3] This doesn't invalidate our classical invariance principles, of course. Rather, the perspectivalist explains that when we typically apply a symmetry we are, in fact, maintaining a single perspective through the transformation. This is reflected in the fact that the symmetry transformations maintain both unitary and non-unitary evolutions.

of classical and relativistic physics that we typically observe.

Taking this position then, the perspectivalist has no responsibility to offer an account of how correlations that appear in the unitary evolution of one perspective can be explained from another. The unitary description of Andrea and Bob from the third-party perspective can be *all there is* to the explanation for their measurement results' correlations.

This may be easier to see if we go back to the case of the non-invasive measurements from chapter 2. There is no difference, of course, between the entanglement that exists between the two photons in the Andrea-Bob case and that of Alice and her qubit. Quantum mechanics doesn't differentiate between 'types' of entanglement. With this in mind, consider the following: Say that instead of measuring Alice's entire lab Wigner measures only Alice (the experimenter) in a basis $\{|A0'\rangle, |A1'\rangle\}$, where the apostrophes represent that these are states of Alice and not the whole lab. Doing so, he could learn what Alice has observed, and in turn, the state of the qubit. (He could also measure the qubit to find Alice's state, of course.)

What is interesting here is that this case doesn't seem to bother us in the same way as the Andrea-Bob one. We don't find it worrisome that by measuring Alice Wigner seems to have 'changed the state' of the qubit she measured. However, this is precisely what troubles us in the case of Andrea's measurement. One might reply that this has to do with the proximity of Alice to her qubit – there's plenty of time for Wigner's measurement of Alice to affect a change in the qubit's state before he then moves on to measuring it (were he to do so). But this is a false comfort, of course. Nowhere in the quantum formalism is there any time differences between Wigner observing his result and the state of Alice's qubit 'changing'. Noting this, the perspectivalist may rightly say that whatever is going on in the case of Andrea and Bob's singlet state pair is exactly the same as the isolated Alice and her qubit. In other words, spacelike separated entangled systems are no more mysterious than timelike separated ones – and neither of these demand action at a distance. Rather we can understand quantum correlations as being entirely guided by the universality of unitary evolution.

5.1.1 Counterfactuals, again

There is one final consequence of this approach which should be clarified here. I mentioned in §3.5 the difficulty that Stairs [72] raises about the use of counterfactuals in the quantum context. Recall: if Andrea and Bob share a singlet state and Andrea measures her particle to be in the state $|0\rangle$, she does seem able to say, "If Bob measured his particle in the computational basis then he observed $|1\rangle$." However, she cannot say, "If Bob *had* measured his particle in the computational basis then he *would have* measured $|1\rangle$."

Given what I've just described, combined with the ontological picture developed, it may seem that the perspectivalist might now disagree with Stairs' conclusion. Consider, for example, that in the encapsulated case if Wigner measures Alice's lab in the $\{|A0'\rangle, |A1'\rangle\}$ basis and observes the result $|A0'\rangle$, this tells him that in Alice's perspective she observed $|0\rangle$. As such, he should be able to say, “Had I measured Alice’s lab a minute before I did, I would have observed the result $|A0\rangle$.” And if this is the case then it would follow in parallel that Andrea could assert the counterfactual about Bob’s outcome too.[4] What I want to outline here are two ways the perspectivalist may go. First, she may differentiate between these cases so as to maintain Stairs’ claim that Andrea’s counterfactual is problematic. Second, she may accept the truth of Andrea’s counterfactual but explain how this doesn’t lead us into a local hidden variable theory. Both approached seem viable pending further details the theorist provides.

5.1.1.1 Differentiating between Alice and Andrea

It does seem that Wigner’s counterfactual here must be true. If Alice observed $|0\rangle$ in her perspective and her result must correlate with Wigner’s, then that it doesn’t matter when Wigner measures her – he will necessary observe $|A0\rangle$. (Indeed, this seems to be equivalent to his saying that her result caused his. Recall that we have permitted that physical possibility may not be a subset of metaphysical possibility.) That said, there may be a way to distinguish between Wigner’s and Andrea’s counterfactuals.

The reason for this, the perspectivalist might explain, is that the measurement we consider in the case of Alice and Wigner is a projection of Alice’s state onto very large subspaces of Hilbert space. We are only concerned with Alice’s

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[4] If the analogy isn’t clear, imagine that Andrea and Bob are superobservers measuring observers who have (already) measured a singlet pair in the computational basis. If Andrea measures her observer to be in a state of having obtained $|0\rangle$, then it feels like she may say, “had Bob measured his observer he would have obtained that she observed $|1\rangle$.

result, not any further details of her state. This is not the case with Andrea and Bob's measurements, of course, as here we are concerned with the exact state of a single particle. This may not seem like an important difference, but consider the following: If Wigner's measurement were not a projection onto these subspaces but rather a measurements of the exact state of the lab, down to the position of each particle, then it certainly seems incorrect to say that he would have gotten the same result had he measured earlier than he did. One way we might explain this is quite simple. Wigner knows that the sequence of quantum measurement results that obtains in the universe forms a classical history, at least at the macroscopic level. When he learns that Alice is in the state $|A0\rangle$ at the time of his measurement, he is also able to infer that for her to be in this state at this time, she must have been in a state that could evolve to it at times between her measurement and Wigner's. Thus, Wigner can assume that were he to have measured her, say a minute earlier than he did, he would have obtained the same result. (Of course, he could only assert the conditional after his measurement, but this isn't problematic for reasons we've seen.)

With this in mind, it is likely clear now how the perspectivalist might deny Andrea's counterfactual about Bob's measurement (and for precisely the same reasons that Stairs suggests).[5]

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[5] Interestingly, this approach might lead to a counterintuitive result about the case described in footnote 4. I'm uncertain about this, however, as this case involves classical histories of spacelike-separated systems. Further investigation is required before a conclusion can be drawn.

5.1.1.2 Biting the counterfactual bullet

The other route the perspectivalist might take is to accept that Andrea's counterfactual is correct but to deny that this leads to trouble. (Note that what I describe here doesn't contradict the first response and indeed, I feel that this second route may be the weaker one.) Again, assume that Wigner's counterfactual about what would have happened if he had measured Alice slightly earlier is true. Importantly though, this is another example of a counterfactual that can be known to Wigner only after he completes his measurement. This may seem entirely unhelpful but note that Wigner can only make one measurement on Alice without changing her state according to quantum mechanics. That is, if she is in the $|A+\rangle$ state and he measures her in any basis that doesn't include $|A+\rangle$ as an eigenvector, quantum mechanics tells him that the probabilities of subsequent measurements will be different. What this means, then, is that if he measures Alice at time t_1 in the basis $\{|A0\rangle, |A1\rangle\}$ and observes the result $|A0\rangle$ he can only know two counterfactuals of the type we've described:

- Had I measured Alice at t_0 in the $\{|A+\rangle, |A-\rangle\}$ basis I would have observed the result $|A+\rangle$.
- Had I measured Alice at t_0 in the $\{|A0\rangle, |A1\rangle\}$ basis I would have observed the result $|A0\rangle$.

Now this looks problematic. It seems as if I've just suggested that Wigner can be certain about two pieces of information simultaneously in a fashion that is precluded by quantum mechanics. However, this is not quite correct. What is demanded by quantum mechanics is that no two measurement outcomes can simultaneously be given probability 1 *by the quantum state*. (C.f. [102, §4] as well as Gleason's theorem [103].) Here we are not deriving the truth of the more than one such certainty from the quantum state. Rather, we are deriving one from the quantum state and one retrodictively from Wigner's actual measurement. Importantly, there is no question about what Alice's quantum state is at any point in time. Wigner's asserting that he knows what would have happened had he measured sooner doesn't change the fact that Alice was in the state $|A+\rangle$ when he actually does measure her. Rather, we can think of this as Wigner asserting that after his measurement he has learned what was observed in Alice's perspective.

Putting aside this worry then, what matters here is that Wigner cannot assert any further counterfactuals about what would happen had he measured Alice earlier. Nor can he make predictions about measurements at t_1 based on the fact that he would have observed $|A0\rangle$ had he measured sooner than he did. This may seem trivial, but it is precisely for this reason that the perspectivalist avoids falling into the local hidden variable trap.

Let's go back to the case of Andrea and Bob. If Andrea measures her particle to be in the state $|0\rangle$ then, in parallel to the above, it seems as if she is able to now say that "had Bob measured his particle in computational basis he would have observed $|1\rangle$." However, this alone need not be problematic. First, it is importantly different from saying that Bob's particle is or has always been in the state $|1\rangle$. Bob's particle is entangled with Andrea's, and all that Andrea is reporting is her certainty about a possible measurement given what she's observed of the system. Second, in the event that Andrea does perform a measurement in the computational basis, she cannot also assert certainty about what Bob would observe were he to measure in any other basis.

It may seem as if my claim here is coming very close to Bohr's reply [104] to Einstein, Podolsky and Rosen (EPR), [105], but I think the perspectivalist has slightly more to say than Bohr does here. Bohr focuses on the physical setup of a measurement apparatus, and specifically on how such setups preclude gaining information about complementary observables. As such, he explains, EPR's *criterion of reality* cannot apply to complementary observables simultaneously. The perspectivalist position is similar, but rather than relying on the physical setup of a measurement device she appeals directly to the universality of unitarity and the Born rule. That is, the perspectivalist takes unitary evolution to be physically fundamental. When Andrea measures her particle in the computational basis she, in a sense, selects a basis in which she will learn about the state of her and Bob's particles. Once she does so though, the laws of quantum mechanics *qua* fundamental descriptions of the observable patterns in the mosaic (and not merely the experimental setup) then determine the probabilities of measurement outcomes that follow. As such, the perspectivalist, for example, blocks EPR's move of simultaneously considering what follows from Andrea's measuring multiple observables.

Putting this together then, the claim is that Andrea's counterfactual may be correct, but this changes nothing about what is predicted or known of Bob's particle, and it certainly doesn't require any action at a distance. Andrea's measurement can be thought of as learning about which possible term in the superposition (of the third-party description) she is in, but in doing so quantum mechanics then provides the probabilities of subsequent measurements.

5.2 Conclusion

There is a sense in which this dissertation has done very little to advance our understanding of quantum mechanics. I have not offered a new theory, nor have I isolated a particular perspectival view as correct. But what I have done here is to demonstrate that the perspectivalist can stand on solid ground. The theory is not the self-contradictory mess that skeptics often claim, nor need it reduce to instrumentalism or some philosophically distasteful position, such as solipsism.

There are some constraints and consequences that come with the view, both good and bad. That consistency should be explained by looking to the fundamental unitary dynamics seems appropriate for a theory that aims to take quantum mechanics as complete. We would not want to have to introduce some consistency-maintaining dynamics that didn't already appear in our physics. At the same time, we've just seen in §5.1 that this means that some physical explanations will be unavailable to some perspectives (although conscious observers in these perspectives will always be able to justify observed correlations by conceptualizing, at least approximately, what another perspective might be describing).

We've also seen that certain arguments against single world theories, such as that raised by Frauchiger and Renner, rely on false premises. Alice cannot make any quantum predictions about measurement on *her*. One interesting part of this response is that a system should never describe itself in any quantum state. This fits well with the central tenets of perspectivalism – every perspective only observes single outcomes of measurement, so it would never observe itself to behave 'quantumly' (and would certainly never observe its own interference terms). What is perhaps more noteworthy about this is that it follows from only Breuer's theorem (which, again, is theory independent) and the assumption that Wigner's application of quantum mechanics to Alice's lab is correct. (We didn't need to assume anything about Alice, and I'm certain that even the Everettian would agree to the conclusion.)

I focused on what I take to be the most important, and perhaps most difficult consequence in §3.7, which is the 'divorce' of ontology from physical dynamics. As explained there, this is an entirely novel suggestion for fundamental physics but not a surprisingly one given the we've maintained a denial of representationalism of the quantum from the start.

Admittedly, there are still questions that remain. For example, I have not discussed how much of a disagreement we might expect between perspectives. We know that Alice and Wigner will disagree about Alice's quantum state, and that Andrea and Bob can disagree in their predictions about Bob's qubit. However, is it possible for two observers to disagree about the state of a system that has decohered into both of their environments? [6]

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[6] I should note that there are some cases which might look to introduce further types of disagreements but which will be immediately answerable. For example, say Andrea and Bob share a singlet state in isolated labs. Alice measures her qubit's spin in the z direction to observe the result $|z+\rangle$, and Bob measures his in the x direction to observe the result $|x\rangle$. We might now

Even with this philosophical ground, though, there is one final hurdle that both skeptic and theorist must accept. We have introduced the Born probabilities from the start; they exist *ex nihilo* as part of the fundamental structure of foundational physics. There is no way to deny that this is unsatisfying for us (as *human* theorists). However, in taking quantum mechanics to be both fundamental and probabilistic, there is simply no way around this.

This is not novel. As Bub notes [39, p.6 & footnote 10], for example, taking probabilities to be reflective of fundamental Hilbert space geometry dates as far back as 1927 with von Neumann's work on the foundations of quantum mechanics.[7] Nonetheless, there has been a great deal of work in quantum causal modeling that attempts to explain the Born probabilities, particularly in cases of entangled systems.[8] These have included everything from hidden variables to exotic retrocausal theories (for example [47, 48, 61]).

Most of this work involves adapting classical causal modeling to the quantum context. But as Fine explains [108], this may be precisely the wrong way to go. We must acknowledge the prior beliefs and experiences that come with our explanatory projects – especially when the object of our attention is meant to be a fundamental physical theory:

> Instead of aiming to demonstrate some limitation or anomaly about

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ask the perspectivalist how to correctly treat this scenario from each perspective. And she can explain: Alice treats Bob as a quantum system, and so Bob's measurement will be described by a unitary evolution. As such, any predictions made about further interactions with Bob or his qubit can correctly treat the qubit as being in the $|z+\rangle$ state. The same applies in the other direction, of course.

[7] See [106] for a highly detailed historical discussion.

[8] For a recent survey on the topic, see Barrett, Lorenz and Oreshkov's [107].

> the theory, this way [of thinking] proceeds in the other direction and helps us understand why the probability structure of the theory is what it is. That understanding comes about when we . . . [let] the indeterminist ideals of the theory set the explanatory agenda. Such an attitude means taking the theoretical givens seriously, and trusting that they will do good explanatory work. Thus, . . . we shift our perspective and use the given quantum correlations . . . to explain why, even in principle, correlations forbidden by the theory cannot arise. [108, p.194]

This is the only coherent position the perspectivalist can offer in response to this hurdle, and it is one she must adopt completely. This is what it *means* to take quantum mechanics and the Born probabilities as fundamental. They are not facts that demand further justification. Rather, they *are* the explanatory building blocks, just as Fine describes. In other words, quantum mechanics doesn't introduce indeterminism and non-locality into an otherwise local, deterministic universe. Rather, the universe is precisely as deterministic and local as quantum physics permits.

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