Quantum Mechanics and the Consistency of Conscious Experience

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(Dated: April 26, 2019)

We discuss the implications for the determinateness and intersubjective consistency of conscious experience in two gedanken experiments from quantum mechanics (QM). In particular, we discuss Wigner’s friend and the delayed choice quantum eraser experiment with a twist. These are both cases (experiments) where quantum phenomena, or at least allegedly possible quantum phenomena/experiments, and the content/efficacy of conscious experience seem to bear on one another. We discuss why these two cases raise concerns for the determinateness and intersubjective consistency of conscious experience. We outline a 4D-global constraint-based approach to explanation in general and for QM in particular that resolves any such concerns without having to invoke metaphysical quietism (as with pragmatic accounts of QM), objective collapse mechanisms or subjective collapse. In short, we provide an account of QM free from any concerns associated with either the standard formalism or relative-state formalism, an account that yields a single 4D block universe with determinate and intersubjectively consistent conscious experience for all conscious agents. Essentially, the mystery in both experiments is caused by a dynamical/causal view of QM, e.g., time-evolved states in Hilbert space, and as we show this mystery can be avoided by a spatiotemporal, constraint-based view of QM, e.g., path integral calculation of probability amplitudes using future boundary conditions. What will become clear is that rather than furiously seeking some way to make dubious deep connections between quantum physics and conscious experience, the kinds of 4D adynamical global constraints that are fundamental to both classical and quantum physics and the relationship between them, also constrain conscious experience. That is, physics properly understood, already is psychology.

Keywords: Wigner’s friend, delayed choice quantum eraser

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I. INTRODUCTION

For a variety of reasons, there is renewed interest in trying to relate conscious experience to quantum mechanics (QM). Usually someone tries to explain one in terms of the other, e.g., the claim that conscious experience collapses the wavefunction \[1\]. There are also many attempts to explain conscious experience in terms of some quantum process or property such as wavefunction collapse, entanglement, etc. Such accounts are metaphysically diverse, ranging from strong emergence, to panpsychism, to dual-aspect theories and beyond \[2\]. Obviously, attempts at explaining some feature of quantum in terms of some feature of conscious experience or vice-versa, require that one be very specific about the interpretation of QM at issue and the particular feature/conception of conscious experience in question. Often when this game is played one assumes that wavefunction realism is true and that qualia is the best way to think about conscious experience. There are of course other ways to relate QM and conscious experience, such as simply using the Hamiltonian formalism of QM to model conscious decision making, e.g., thinking thru a decision is like being in a superposition state and making a decision is wavefunction collapse \[2\].

More generally, Gao argues that the very measurement problem itself should be characterized as a problem about determinate-experience

\[\text{[t]he problem is not only to explain how the linear dynamics can be compatible with the appearance of definite measurement results obtained by physical devices, but also, and more importantly, to explain how the linear dynamics can be compatible with the existence of definite experiences of conscious observers [3, p. 4].}\]

Of course one could certainly push back on Gao’s characterization of the measurement problem. Many would argue that the measurement problem would exist even in a world with no conscious observers or that there are interpretations of QM that yield definite classical outcomes and thus determinate experiences. However, if one assumes wavefunction realism as Gao does and one adopts some no collapse interpretation of QM, then it is certainly reasonable to raise the question of why and how we have determinate experiences. Even though one may be convinced in general that no-collapse interpretations such as Many-Worlds and Bohmian mechanics have no such concern, it is this question of determinate experience and intersubjectively consistent determinate experience that we shall take up herein. This is because, as we are all well aware, there are cases (experiments) where, at least on certain interpretations, there is a problem about determinate and intersubjectively consistent experience. In such cases quantum phenomena or at least allegedly possible quantum phenomena/experiments and the content/efficacy of conscious experience seem to bear on one another. That is, what you say about one side of the story has logical/physical implications for the other side. Herein we will look at two such cases: Wigner’s friend and delayed choice quantum eraser with a twist. We will discuss why these cases raise concerns for the determinateness and intersubjective consistency of conscious experience.

The specific question we want to address is as follows: is there an account of QM that explains why there is determinate, objective experience and intersubjectively consistent determinate experience about all experimental outcomes, that requires no invocation of relative states (e.g., outcomes being relative to branches, observers, etc.), that requires no objective collapse mechanism as with the standard model, and requires no allegedly hybrid models such as claims about “subjective collapse?” We want an account that provides a single world wherein all the observers agree about the determinate outcomes, because those outcomes are in fact determinate and definite, but without having to add some collapse mechanism with all the attending problems such mechanisms bring.

Herein, we will introduce such an account of QM (for more details see \[4\]). The key to such an account is transcending the idea that dynamical explanation (e.g., the evolution of the wavefunction in Hilbert space) is realistic and fundamental. As desired, our approach avoids the pitfalls of either relative-state approaches or standard formalism approaches. We will outline a 4D-global constraint-based approach to explanation in general and in QM in particular that resolves all such concerns. What will become clear is that rather than furiously seeking some way to make dubious deep connections between quantum physics and conscious experience, the kinds of 4D adynamical global constraints that are fundamental to both classical and quantum physics and the relationship between them, also constrain conscious experience. That is, physics properly understood, is psychology already.

In order to appreciate how 4D-constraint-based explanation works in QM and how it can resolve our concerns, we provide an overview and an introduction to the very idea itself in section \[11\] starting with relativity in particular, where it easiest to see the essence of such explanations. It will become clear that such constraints are not primarily about logical consistency, but about spatiotemporal physical consistency. We then show how all this bears on the relationship between the classical and the quantum. More specifically, we show that the quantum and the classical are interdependent per “quasi-separability.” In section \[11\] before returning to the quantum, we return to general relativity to drive home the nature of adynamical constraint-based explanation. With all that in hand, in sections \[IV\] and \[VI\] we apply our approach to the Wigner’s friend and delayed choice quantum eraser gedanken experiments, respectively, showing why our approach has none of the concerns about determinate and intersubjectively consistent
experience that some other approaches have. We will also make it clear why our 4D-global constraint-based model has no measurement problem, no non-locality and a very natural explanation of the Born rule. We conclude in section VII with a more general discussion of the relationship between QM and conscious experience on our view. In part because we reject realism about the wavefunction and we reject the conception of conscious experience in terms of qualia, we are skeptical that either QM or conscious experience so conceived explain one another in any direct fashion, but we do provide an alternative model of how conscious experience and the physical world relate via a kind of neutral monism, wherein again, the mental and the physical are not disparate realms that require magical acts of radical emergence or little minds hiding in the center of subatomic particles.

II. CONSTRAINT-BASED EXPLANATION

Before we can explain how the Wigner’s friend and delayed choice quantum eraser gedanken experiments of QM bear on conscious experience per our constraint-based approach to physics, we must provide some background. Our perceptions are formed dynamically, i.e., in a causal, temporally sequential fashion, as in a game of chess. For example, move number 25 cannot be made until all moves 1 – 24 have been made. Therefore, move number 25 can be said to be explained by move number 24 which is explained by move number 23, etc. In contrast, the answers to a crossword puzzle explain each other, no word has any explanatory priority over the other words. A crossword puzzle is analogous to what we mean by “adynamical” or “constraint-based” explanation. The goal in a crossword puzzle is a self-consistent collection of intersecting words in accord with the clues (constraints) given. We propose interpreting modern physics in analogous fashion where the constraints in physics will be spatiotemporal. Ironically perhaps, the adynamical global constraints in question actually guarantee a sensible world of classical/dynamical objects that, from the “ant’s-eye perspective” [5], evolve in space and time. That is, classical/dynamical objects (things that persist), time, and space are all interdependent. In short, we will explain why, on our view, this is and must be a world with determinate experience and universal intersubjective agreement.

The adynamical approach we advocate employs constraints over the block universe, which is summed up nicely by Geroch, from a “God’s-eye view” [4] as it were

There is no dynamics within space-time itself: nothing ever moves therein; nothing happens; nothing changes. In particular, one does not think of particles as moving through space-time, or as following along their world-lines. Rather, particles are just in space-time, once and for all, and the world-line represents, all at once, the complete life history of the particle [6, p. 20–21].

A constraint for classical physics over the block universe is provided by Einstein’s equations of general relativity

\[ G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta} \]  

where

\[ G_{\alpha\beta} = R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R + \Lambda g_{\alpha\beta} \]  

Typically, the goal is to obtain the metric \( g_{\alpha\beta} \) in the Einstein tensor \( G_{\alpha\beta} \) on the left side, where \( g_{\alpha\beta} \) provides the geometry on the spacetime manifold \( M \). Einstein’s equations tell you that in order to find the metric, you need the stress-energy tensor \( T_{\alpha\beta} \) on the right side. But, you cannot input force, momentum, and energy for the stress-energy tensor unless you know how to make spatiotemporal measurements, i.e., unless you have the metric. Thus, solutions of Einstein’s equations are simply self-consistent sets of spatiotemporal measurement, force, momentum, and energy on the spacetime manifold \( M \), as with the words in a crossword puzzle. In this sense, Einstein’s equations of general relativity provide an adynamical global constraint for spatiotemporal measurement, force, momentum, and energy on the spacetime manifold \( M \), i.e., Einstein’s equations provide an adynamical global constraint for the block universe. This adynamical global constraint is motivated by a fundamental, empirical fact, i.e., the existence of classical objects, as follows.

\( G_{\alpha\beta} \) is the most general form of the metric with its first and second-order derivatives that is divergence-free, so we have

\[ \nabla^\gamma G_{\alpha\beta} = \nabla^\gamma T_{\alpha\beta} = 0 \]  

This means \( T_{\alpha\beta} \) is divergence-free, which expresses the local conservation of energy-momentum per special relativity.

All of this follows from a geometric tautology called the “boundary of a boundary principle,” i.e. \( \partial \partial = 0 \), which also

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1 General relativity reduces to special relativity locally per the equivalence principle.
underwrites electromagnetism [7] p. 364 [8]. The divergence-free nature of $T_{\alpha\beta}$ is consistent with the fundamentality of time-evolved or “diachronic” entities in dynamical narration, i.e., objects with worldlines in spacetime. Thus, this adynamical global constraint is motivated by fundamental notions of space, time and diachronic entities (aka “classical objects”). Indeed, there is no principle which dictates the construct of classical objects fundamental to the formalism of dynamics in general – these objects are “put in by hand” throughout physics. When Albrecht and Iglesias [9] allowed time to be an “internal variable” after quantization, as in the Wheeler-DeWitt equation, they found “there is no one set of laws, but a whole library of different cosmic law books” [10]. They called this the “clock ambiguity.” In order to circumvent this “arbitrariness in the predictions of the theory” they proposed that “the principle behind the non-relativistic Klein-Gordon equation giving the free-particle Schrödinger equation by factoring out the rest mass contribution to the energy $E$, assuming the Newtonian form for kinetic energy, and discarding the second-order time derivative [12, p. 172]. To illustrate the first two steps, plug $\phi = Ae^{i(px-Et)/\hbar}$ into the Klein-Gordon equation and obtain $(-E^2 + p^2 c^2 + m^2 c^4) = 0$, which tells us $E$ is the total relativistic energy. Now plug $\psi = Ae^{i(px-Et)/\hbar}$ into the free-particle Schrödinger equation and obtain $\frac{\hbar^2}{2m} = E$, which tells us $E$ is only the Newtonian kinetic energy. Thus, we must factor out the rest energy of the particle, i.e., $\psi = e^{imc^2t/\hbar}\phi$, assume the low-velocity limit of the relativistic kinetic energy, and discard the relevant term from our Lagrangian density (leading to the second-order time derivative) in going from $\phi$ of the Klein-Gordon equation to $\psi$ of the free-particle Schrödinger equation. We will simply outline the details here.

Overall, we start with a transition amplitude from quantum field theory to get our generating function whence the idea that individual entities exist at all” [10]. Albrecht and Iglesias characterize this as “the central role of quasi-separability” [11]. This means any given classical object can be decomposed into quantum interactions with all the other classical objects in its classical environment (contextuality), i.e., there is no ‘global’ quantum decomposition. All this brings us to the role of quantum physics in our crossword puzzle.

The classical objects of classical physics interact per quantum physics, so the quantum exchange of energy-momentum between classical objects per QM must be consistent with their divergence-free nature. This fact is represented by gauge fixing per gauge invariance. We can illustrate that by using the non-relativistic limit of the Klein-Gordon equation giving the free-particle Schrödinger equation by factoring out the rest mass contribution to the energy $E$, assuming the Newtonian form for kinetic energy, and discarding the second-order time derivative [12, p. 172].

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We start with a transition amplitude from quantum field theory to get our generating function whence the propagator that gives us the QM probability amplitude $\psi$. The transition amplitude for the Klein-Gordon equation is

$$Z(J) = \int D\phi \exp \left[ \frac{i}{\hbar} \int d^4x \left( \frac{1}{2} (\partial\psi)^2 - \frac{1}{2} m^2 \phi^2 + J\phi \right) \right]$$

which in (1+1)D is

$$Z(J) = \int D\phi \exp \left[ \frac{i}{\hbar} \int dx dt \left( \frac{1}{2} \left( \frac{\partial\phi}{\partial t} \right)^2 - c^2 \left( \frac{\partial\phi}{\partial x} \right)^2 - \frac{1}{2} m^2 \phi^2 + J\phi \right) \right]$$

where $m = \frac{mc^2}{\hbar}$. Making the changes described above with $\psi = e^{imc^2t/\hbar}\phi$ gives the non-relativistic Klein-Gordon transition amplitude corresponding to the free-particle Schrödinger equation [12] p. 173]

$$Z(J) = \int D\psi \exp \left[ \frac{i}{\hbar} \int dx dt \left( i\psi^* \frac{\partial\psi}{\partial t} - \frac{c^2}{2m} \left( \frac{\partial\psi}{\partial x} \right)^2 + J\psi \right) \right]$$

Now integrate the second term by parts and obtain

$$Z(J) = \int D\psi \exp \left[ \frac{i}{\hbar} \int dx dt \left( i\psi^* \frac{\partial\psi}{\partial t} + \frac{\hbar}{2m} \psi^* \frac{\partial^2\psi}{\partial x^2} + J\psi \right) \right]$$

This gives

$$Z(J) = \int D\psi \exp \left[ \frac{i}{\hbar} \int dx dt \left( \frac{1}{2} \psi^* K\psi + J\psi \right) \right]$$

where

$$K = \left( 2\frac{\partial}{\partial t} + \frac{\hbar}{m} \frac{\partial^2}{\partial x^2} \right)$$

Discretizing this on a four-node graph, for example, we find that $K$ is given by
\[ K = \begin{pmatrix}
\left(\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) & \left(-\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) & \frac{h}{m \Delta x^2} & 0 \\
\frac{2i}{\Delta t} & \frac{h}{m \Delta x^2} & 0 & \left(-\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) \\
0 & \frac{h}{m \Delta x^2} & 0 & \left(\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) \\
\left(\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) & \left(-\frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\right) & \frac{h}{m \Delta x^2} & 0 
\end{pmatrix} \] (10)

The eigenvalues are \( \{0, \frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}, \frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}, \frac{2i}{\Delta t} - \frac{h}{m \Delta x^2}\} \) with eigenvectors \((1,1,1,1), (-1,1,-1,1), (-1,-1,1,1), \) and \((1,-1,-1,1)\), respectively. This is a Hadamard structure that we see repeated in \( K \) for the Klein-Gordon and Dirac equations [13].

We call \( K \) the "relations matrix" because the rows of \( K \) sum to zero. For example, if we were describing the line of people \([\text{Alice}, \text{Bob}, \text{Charlie}, \text{David}]\), we would say, "Alice is in front of Bob" and "Bob is behind Alice and in front of Charlie." Assigning a numerical value of +1 to "in front of" and -1 to "behind," we see that adding the statements describing the locations of all four people gives a result of zero. This "summing to zero" happens because we have a self-referential, relational description of all four people. Mathematically we write \( K \cdot [1111]^T = 0 \) and say that \([1111]^T\) is a non-null eigenvector of \( K \) with eigenvalue zero and \( K \) is said to possess a non-trivial null space. The complement to that non-trivial null space is called the "row space" of \( K \) because we have a self-referential, relational description of all four people. Mathematically we write \( K \cdot [1111]^T = 0 \) and say that \([1111]^T\) is a non-null eigenvector of \( K \) with eigenvalue zero and \( K \) is said to possess a non-trivial null space.

III. ADYNAMICAL EXPLANATION FOR GENERAL RELATIVITY

We cannot provide the details of how our adynamical explanation in the block universe resolves many of the puzzles, problems, paradoxes, and conundrums of modern physics; to do so required an entire book [4]. However, we must provide an example of this constraint-based explanation because it is essential for our explanations of the QM experiments that follow. Let us briefly consider mysteries associated with general relativity.

In Big Bang cosmology, we have the well-known problem of inexplicable initial conditions, e.g., low entropy, spatial flatness, and the isotropy of background radiation. This results from dynamical explanation where conditions at any location on \( M \) are said to be explained by previous conditions on \( M \) alone, leaving initial conditions (potentially)

\[ ^2 \text{QM interactions are also based on no preferred reference frame} \] [19].

\[ ^3 \text{The postulates of special relativity leading to the relativity of simultaneity, for example. Or, the Tsirolelson bound from conservation per no preferred reference frame} \] [16], an ‘average-only’ conservation principle realized only in 4D not on a trial-by-trial basis.
unexplained and therefore (potentially) “mysterious.” Again, dynamical explanation is like a game of chess where move 25 is explained by move 24 which is explained by move 23, etc. As stated by Wilczek, “The account it gives – things are what they are because they were what they were – raises the question, Why were things that way and not any other?” [5, p. 37] In many non-cosmological situations, such as an experiment in a lab, a human agent is responsible for establishing the initial conditions, so the initial conditions are explicable and certainly not mysterious. But in Big Bang cosmology, the initial conditions are totally inexplicable per prior conditions (by definition) and thus totally mysterious per dynamical explanation. In order to “save the appearances” some diehard dynamists have invoked non-human external agents like God, but this is certainly beyond the realm of physics. Others have assumed M is part of another spacetime structure, but this merely “kicks the can down the road.” Such desperate measures can easily be avoided by our constraint-based explanation as follows.

While a Big Bang solution may be created in the time-evolved fashion of dynamical thinking, the solution itself, i.e., self-consistent metric and stress-energy tensor on M, is just “once and for all.” Viewing general relativity in this fashion we understand that its solutions are spatiotemporally global. Accordingly, like a crossword puzzle, no place on M has any explanatory priority over any other place on M. Any event in M with Einstein’s equations can be used to explain the other events in M, analogous to a crossword puzzle. While it is certainly the case that dynamical stories on M can be told using the metric and stress-energy tensor, such dynamical stories are not fundamental on our view. Instead, the spatiotemporally global solution based on self-consistency is fundamental. If there are any locations on M, such as initial conditions for Big Bang cosmology, that do not allow for dynamical explanation, then the existence and character of those locations are understood only adynamically, as required by the adynamical global constraint per self-consistency with all other events on M, even if the solution was obtained using dynamical methods. So, the situation at any point on M is contingent per the adynamical global constraint on the situation at points elsewhere on M. No point on M is the ultimate basis of explanation on our view, no point on M is ultimately any more or less special than any other. As summed up by Crowther, “everything is the way it is because everything is the way it is in accordance with the adynamical global constraint” [17].

In summary, these mysteries arise because the dynamical bias of our time-evolved, causal perception demands dynamical explanation, and a dynamical story about the universe traced backwards in time leads ultimately to conditions in the very early universe. The key to avoiding this explanatory problem is to relegate dynamical explanation based on time-evolved stories to secondary (non-fundamental) status and accept that the more general constraint-based explanation with its adynamical global constraint is truly fundamental. This is adynamical explanation for modern physics. While time-evolved stories can certainly be told in general relativity solutions, there well may be events in a general relativity solution that resist such dynamical explanation, e.g., the origin of the universe or “Why were things that way and not any other?” In those cases, we just have to accept that modern physics is best understood adynamically in spatiotemporally holistic fashion. As Wharton says

When examined critically, [dynamical explanation] is exactly the sort of anthropocentric argument that physicists usually shy away from. It’s basically the assumption that the way we humans [experience reality] must be the way the universe actually operates [18, p. 177].

In the next section we want to apply this sort of adynamical global constraint thinking to a case that, at least on some interpretations of QM, threatens the possibility of a single universe with determinate outcomes and complete intersubjective agreement.

IV. ADYNAMICAL EXPLANATION FOR WIGNER’S FRIEND

We introduce the quantum mechanical gedanken experiment called “Wigner’s friend” using Healey’s version [19] of Frauchiger & Renner’s version [20] of Wigner’s original version [21]. The whole point of the Wigner’s friend scenario is that someone (Wigner in the original story) makes a quantum measurement of someone else (Wigner’s friend) who made a measurement of some quantum system. For that to be possible, Wigner’s friend must be isolated (screened off) from Wigner and the rest of the universe[4]. Being screened off means Wigner’s friend cannot share any classical information with the universe. This introduces crucial (but often ignored) technical and conceptual difficulties.

Technically, one would have to keep Wigner’s friend and his entire lab from interacting with the universe, e.g., no exchange of photons. That’s certainly beyond anything we can do now, but more importantly, this means the classical information possessed by the friend[5] with lab while screened off is not accessible to Wigner or anyone else in the block universe. Since the block universe is precisely all shared, self-consistent classical information, the friend’s classical

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4 The term “universe” is taken to mean a spatial hypersurface in a block universe foliation as generated, say, by cosmological proper time.
5 The classical information could just as well be contained in a computer with no human agent involved.
information while screened off, being unshared/unaccessible to everyone else, is not even part of the block universe and therefore not a part of objective reality. And that means, among other things, that there is no way to establish relative coordinate directions between Wigner’s frame and his friend’s frame. Accordingly, it would be impossible to relate Hilbert space vectors involving, say, polarizer orientations between the two isolated frames. Thus, after being measured by Wigner, it is impossible for the friend’s classical results to contradict the shared classical information of the block universe, as required to refute objective reality.

Conceptually, if Wigner’s friend is measuring \( \hat{x} \) with the eigenbasis |heads⟩ and |tails⟩ (a “quantum coin flip”), it must be possible for Wigner to measure \( \hat{w} \) with the eigenbasis |heads⟩ − |tails⟩ and |heads⟩ + |tails⟩, even though we cannot imagine what that means in terms of a coin flip. In QM, every Hilbert space basis rotated from the eigenbasis of some measurement operator is the eigenbasis of some other measurement operator and therefore constitutes something we can measure, e.g., Stern-Gerlach magnets or polarizers rotated in space giving rise to rotated eigenbases in Hilbert space.

As we will show, the tacit introduction of these inconsistencies is what leads to the inconsistencies (inconsistent, shared classical information in the form of shared measurement outcomes) associated with the Wigner’s friend experiment. And, as Baumann & Wolf (BW) show and we will introduce, there are other approaches to QM which do not suffer such inconsistencies.

Thus, the bottom-line question for the Wigner’s friend experiment is whether or not a person (such as Wigner’s friend) making a quantum measurement can themselves be treated consistently as a quantum system by someone else (such as Wigner). As we will see, the answer is “yes,” as long as the friend does not share classical information with the universe while screened off, i.e., while being treated as a quantum system. So, there is no size limit to the applicability of QM as some have asserted based on FR. The problem is, the way Wigner’s friend is typically cast, the friend employs a measurement-update rule while Wigner assumes the friend and his lab (to include their measurement records and memories) continue to evolve unitarily per the Schrödinger equation. BW call this “subjective collapse” and show that even in the simplest version of Wigner’s friend, the sharing of inconsistent classical information can result. We will provide a similar example below. According to our constraint-based explanation, since this possibility allows for self-inconsistent shared classical information, the answer to this bottom-line question is “no” under these circumstances. The whole point of the constraint in the block universe (such as Einstein’s equations) is to ensure that the shared classical information composing the block universe is self-consistent. We begin with a presentation of Wigner’s friend per Healey showing how subjective collapse leads to the sharing of inconsistent classical information. Then we will show how proper treatments per the “standard” and “relative-state” formalisms for QM contain no such inconsistency.

There are four agents in this story – Xena who makes a quantum measurement \( \hat{x} \) on quantum state \( \psi \) in her lab X and then sends a quantum state \( s \) to Yvonne, Yvonne who makes a quantum measurement \( \hat{y} \) on \( s \) in her lab Y, Zeus who makes a quantum measurement \( \hat{x} \) or \( \hat{y} \) on X pertaining to Xena’s \( \hat{x} \) measurement, and Wigner who makes a quantum measurement \( \hat{w} \) or \( \hat{y} \) on Y pertaining to Yvonne’s \( \hat{y} \) measurement. So, we have two “Wigners,” i.e., Zeus and Wigner, and two “Wigner’s friends,” i.e., Xena (Zeus’s friend) and Yvonne (Wigner’s friend). The first assumption of FR is that it is possible for Xena and Yvonne to behave as quantum systems for Zeus and Wigner to measure, i.e., there are no size restrictions on what can behave quantum mechanically. Again, we agree that it is possible to screen off Xena and Yvonne with the caveat that, in Bub’s language, those systems being treated quantum mechanically per non-Boolean algebra are not exchanging classical information with the universe per Boolean algebra. We now explore the implications of violating that caveat via subjective collapse as in FR. The starting state \( \psi \) for Xena is

\[
\frac{1}{\sqrt{3}}|\text{heads}\rangle + \frac{\sqrt{2}}{\sqrt{3}}|\text{tails}\rangle
\]  

(11)

The eigenbasis for Xena’s \( \hat{x} \) measurement is simply |heads⟩ and |tails⟩ with eigenvalues heads and tails, respectively. If the outcome of her measurement is heads, she sends state \( s \)

\[
|\rangle
\]  

(12)

to Yvonne. If the outcome of her measurement is tails, she sends state \( s \)

\[
\frac{1}{\sqrt{2}}(|\rangle + |\rangle)
\]  

(13)

6 This is another crucial point that is ignored in analyses of Wigner’s friend, but as we will see in section \[22\] Proietti et al. have shed some light on it.

7 This is sometimes associated with “wavefunction collapse.”
to Yvonne. Again, if $|+\rangle$ and $|-\rangle$ refer to orientations in space, e.g., polarizers or Stern-Gerlach magnets, their meaning between Xena and Yvonne is problematic, since their labs are isolated from one another. The sharing of such classical information is crucial for the modeling of the block universe as we have defined it per the very meaning of the Hilbert space structure, so ignoring this point is to introduce an inconsistency. But, as with the original papers, we will proceed to find its implications.

The second assumption of FR is that there is only one outcome for a quantum measurement. So, for example, Xena does not measure both heads and tails and send both versions of state $s$. Now, assuming the subjective-collapse model, Xena and Yvonne’s labs are behaving quantum mechanically (evolving unitarily) according to Zeus and Wigner, so they are entangled in the state

$$|\Psi\rangle = \frac{1}{\sqrt{3}} (|\text{heads}|\rangle - |\text{tails}|\rangle + |\text{tails}|\rangle)$$

per Eqs. (11), (12) and (13) for Zeus and Wigner (this is Eq. (13) in Healey’s paper). Assuming Xena and Yvonne’s labs evolve unitarily means Zeus and Wigner can make measurements of Xena and Yvonne’s labs in any rotated Hilbert space basis they choose. In addition to the measurement $\hat{x}$ with eigenbasis $|\text{heads}\rangle$ and $|\text{tails}\rangle$, Zeus has the option of measuring $\hat{z}$ with eigenbasis

$$|\text{OK}\rangle_Z = \frac{1}{\sqrt{2}} (|\text{heads}\rangle - |\text{tails}\rangle)$$
$$|\text{fail}\rangle_Z = \frac{1}{\sqrt{2}} (|\text{heads}\rangle + |\text{tails}\rangle)$$

And, in addition to the measurement $\hat{y}$ with eigenbasis $|+\rangle$ and $|-\rangle$, Wigner has the option of measuring $\hat{w}$ with eigenbasis

$$|\text{OK}\rangle_W = \frac{1}{\sqrt{2}} (|+\rangle - |-\rangle)$$
$$|\text{fail}\rangle_W = \frac{1}{\sqrt{2}} (|+\rangle + |-\rangle)$$

Again, this introduces another inconsistency with the block universe of shared, self-consistent classical information, i.e., the classical information must be intelligible. First, we have already pointed out how the relative orientations of Stern-Gerlach magnets or polarizers are needed to make sense of Wigner’s measurements of Yvonne’s lab and that this constitutes shared classical information forbidden by the assumption that Yvonne’s lab is screened off from Wigner. Second, we also have a problem of intelligibility between Zeus and Xena as mentioned above. That is, the eigenbasis $|\text{heads}\rangle - |\text{tails}\rangle$ and $|\text{heads}\rangle + |\text{tails}\rangle$ makes no sense and without that understanding, it is impossible to create a block universe experimental configuration of classical information corresponding to this Hilbert space basis.

8 See section concerning progress on this question from Proietti et al. [22].
and Yvonne. That is, each of the three individual possibilities of heads and -1 or tails and +1 or tails and -1 is compatible with an OK outcome for Zeus’s \( \hat{z} \) measurement. But when Zeus obtains OK, Wigner must obtain +1 for a \( \hat{y} \) measurement, since \( \langle \Psi | OK \rangle_Z = -\frac{1}{\sqrt{6}} \langle + \rangle \), which rules out the possibility that the prior configuration of Xena and Yvonne was heads and -1 or tails and -1, respectively, and that contradicts our assumption that \( |\Psi\rangle \) is the quantum state for Zeus and Wigner for any of the definite configurations for Xena and Yvonne prior to Zeus and Wigner’s measurements. Obviously, our mistake is to assume classical definiteness for a quantum system. You can see that we have a QM interference effect by rewriting Eq. (14) as

\[
|\Psi\rangle = \frac{1}{\sqrt{3}} \left( \sqrt{2} |\text{fail} \rangle_Z |\text{tails} \rangle + |\text{tails} \rangle |\text{fail} \rangle_W \right)
\]

Likewise, suppose Wigner first measures \( \hat{w} \) and obtains OK (eigenvalue for \( |OK\rangle_W \)), which can certainly happen since Yvonne measured either +1 or -1, i.e., each of the three individual possibilities of heads and -1 or tails and +1 or tails and -1 is compatible with an OK outcome for Wigners \( \hat{w} \) measurement. But, when Wigner obtains OK, Zeus must obtain heads if he measures \( \hat{x} \), since \( \langle \Psi | OK \rangle_Y = -\frac{1}{\sqrt{6}} \langle \text{heads} \rangle \), which rules out tails and +1 or tails and -1 as possible prior configurations for Xena and Yvonne, respectively, contrary to our assumption. Again, QM interference is at work, which you can see by rewriting Eq. (14) as

\[
|\Psi\rangle = \frac{1}{\sqrt{3}} \left( |\text{heads} \rangle |\text{fail} \rangle_W + |\text{tails} \rangle |\text{fail} \rangle_W \right)
\]

Now let us show explicitly what kind of shared, self-inconsistent classical information can result for the inconsistent assumptions involved in this subjective-collapse experiment.

Suppose Xena measures the state

\[
\frac{1}{\sqrt{2}} \left( |\text{heads} \rangle + |\text{tails} \rangle \right)
\]

in the basis \( |\text{heads} \rangle, |\text{tails} \rangle \). Further, suppose that if Xena obtains heads, she sends the state \( |\text{heads} \rangle \) to Wigner who likewise does a measurement in the basis \( |\text{heads} \rangle, |\text{tails} \rangle \). Conversely, if Xena measures tails, she sends the state \( |\text{tails} \rangle \) to Wigner who again does a measurement in the basis \( |\text{heads} \rangle, |\text{tails} \rangle \). This constitutes sending classical information of course, which is essentially what is done in FR’s approach. Now, Zeus passes Xena and her lab through a ‘heads-tails polarizer’ \( \langle |\text{heads} \rangle + |\text{tails} \rangle \rangle \) and then does a measurement in the the basis \( |\text{heads} \rangle, |\text{tails} \rangle \). Of course, it is entirely possible that Zeus’s final measurement will yield tails. Keep in mind that Zeus’s outcome is classical information about Xena’s entire recorded history to include Xena’s memories of the entire process. Therefore, Xena’s records and memories will show that she measured tails and sent \( |\text{tails} \rangle \) to Wigner. Consequently, Wigner must have a classically written record of tails for his outcome. But, of course, Wigner’s classical information is heads, so we do not have a self-consistent collection of classical information being shared between Xena, Zeus, and Wigner. BW call this a “scientific contradiction” and state that it “must not arise for a scientific theory.” We concur of course. So, how would the standard formalism of QM deal with this?

In the standard formalism per BW, everyone agrees that all measurements produce a collapse, i.e., measurement update is objective. Therefore, Xena and Yvonne’s measurement outcomes constitute classical information that cannot be treated quantum mechanically if it is going to be shared as part of the block universe. [Of course, one could argue that “unshared classical information” is an oxymoron, but that is a semantic point with ontological implications that we will not engage here.] Recall, a screened-off system is not part of the block universe/objective reality by definition. However, that does not mean we cannot screen off an entire lab and then treat it quantum mechanically. It is simply the case that the screened-off lab cannot interact with the universe, since that creates the possibility of inconsistent, shared classical information in the block universe which constitutes a scientific contradiction. Therefore, the exchanges needed in FR to create the inconsistencies are the cause of the inconsistencies.

This is where our constraint-based explanation would stand, since all classical information is to be represented in the block universe in self-consistent fashion. But, there is no collapse on our view nor any question about how or when or why collapse happens. We construct a realistic psi-epistemic account of QM [15]. If one constructs the differential equation (Schrödinger equation) corresponding to the Feynman path integral, the time-dependent foliation of spacetime gives the wavefunction \( \Psi(x,t) \) in concert with our time-evolved perceptions and the fact that we do not know when the outcome is going to occur. Once one has an outcome, both the configuration \( x_o \), that is the, specific spatial locations of the experimental outcomes, and time \( t_o \), of the outcomes are fixed, so the wavefunction \( \Psi(x,t) \) of configuration space \([3]\) becomes a probability amplitude \( \Psi(x_o,t_o) \) in spacetime, i.e., a probability amplitude for
a specific outcome in spacetime. Again, the evolution of the wavefunction in configuration space before it becomes a probability amplitude in spacetime is governed by the Schrödinger equation. However, the abrupt change from wavefunction in configuration space to probability amplitude in spacetime is not governed by the Schrödinger equation. In fact, if the Schrödinger equation is universally valid, it would simply say that the process of measurement should entangle the measurement device with the particle being measured, leaving them both to evolve according to the Schrödinger equation in a more complex configuration space (as in the relative-states formalism shown below). However, modulo the Many-Worlds interpretation, we do not seem to experience such entangled existence in configuration space, which would contain all possible experimental outcomes. Instead, we experience a single experimental outcome in spacetime. This contradiction between theory and experience is called the “measurement problem” for Gao. However, the time-evolved story in configuration space is not an issue with the path integral formalism as we interpret it, because we compute \( \Psi(x_0, t_0) \) directly. That is, in asking about a specific outcome we must specify the future boundary conditions that already contain definite and unique outcomes. Thus, the measurement problem is a non-starter for us. When a QM interpretation assumes the wavefunction is an epistemological tool rather than an ontological entity, that interpretation is called “psi-epistemic.” In our path integral constraint-based account, the wavefunction in configuration space is not even used, so our account is trivially psi-epistemic. But, one must also understand the classical-quantum contextual implications of our view.

As we suggested in our initial discussion about the relationship between the classical and the quantum, the presumably classical experimental setup (or the many analogs of that in a natural setting) cannot be reduced away and plays an absolutely essential role in explaining so-called quantum outcomes; that is, the experimental setup must be treated as classical in order to use QM. This abandonment of foundationalism may strike many readers as beyond reasonable, but it is nothing new in the history of QM. So again, for us the fundamental explanatory role goes to what we call an adynamical global constraint applied to the spatiotemporal distribution of outcomes. Because of our hunch about an adynamical global constraint being fundamental, we based our account on the path integral formalism and seek a realist account with a single history. The point is that for us, the very idea that something could be both truly screened-off from the rest of the block universe and also meaningfully treated classically, makes no sense.

Suppose there exists a “quantum entity” with some set of causal properties traversing the space between the source and detector to mediate a quantum exchange. According to environmental decoherence, this quantum entity cannot interact with its environment or it will cease to behave quantum mechanically, for example, it will act as a particle instead of a wave and cease to contribute to interference patterns. Now if this quantum entity does not interact in any way with anything in the universe (it is screened off), then it is not exchanging bosons of any sort with any object in the universe of classical physics. Thus, it does not affect the spacetime geometry along any hypothetical worldline (except at the source and detector) according to Einstein’s equations (or it would be interacting gravitationally, i.e., exchanging gravitons). Accordingly, there cannot be any stress-energy tensor associated with the worldline of this quantum entity any place except at the source and detector. So, practically speaking, this posited “screened-off quantum entity” is equivalent to “direct action.” Thus, according to our view, QM is simply providing a probability amplitude for the 4D distribution of outcomes in the QM experiment. That is, in our view there are no “QM systems” such as waves, particles, or fields that exist independently of spatiotemporal, classical contexts. As Feynman puts it

> In the customary view, things are discussed as a function of time in very great detail. For example, you have the field at this moment, a different equation gives you the field at a later moment and so on; a method, which we shall call the Hamiltonian method. We have, instead [the action] a thing that describes the character of the path throughout all of space and time . . . . From the overall space-time point of view of the least action principle, the field disappears as nothing but bookkeeping variables insisted on by the Hamiltonian method.\(^{[25]}\) p. xv].

Given our psi-epistemic account of QM with unmediated exchanges/direct action (i.e., there are no worldlines of counterfactual definiteness that connect the source and the detector), there is no “screened off quantum entity” that must decohere to behave classically. So on our view, environmental/dynamical decoherence is really just a dynamical take on what is in fact spatiotemporal contextuality. What QM is really telling us is that to exist (i.e., to be a classical information constituting the block universe. Consistent with this quantum-classical ontology is the distinction between quantum and classical statistics, as characterized by the Born rule. That is, one adds individual amplitudes then squares to get the probability, rather than squaring each amplitude then adding as in classical probability, e.g., statistical mechanics. The quantum exchange of energy-momentum between classical objects requires cancellation of possibilities and the path integral whereby the spacetime path of extremal action (classical trajectory) is obtained by interference of non-extremal possibilities which contribute with equal weight.\(^{[26]}\) p. 224-225]. Classical statistics does not provide for this so-called quantum interference. In fact, on our view the reason classical statistics works for classical objects is precisely because a classical object is a set of definite (high probability) quantum exchanges in the context of all other classical objects, as we just
explained. That is, classical statistics assumes a distribution of classical objects and any given classical object can be viewed as obtaining from quantum statistics in the context of all other classical objects, having removed non-extremal possibilities via quantum interference. Therefore, classical statistics follows from quantum statistics as the quantum exchange of energy-momentum must be in accord with the classical objects of the block universe. Again, since our model of objective reality is based on 4D-global self-consistency, the quantum/classical is not more fundamental than the classical/quantum – they require each other (Figure 1).

As with all the other mysteries of QM, the Born rule is vexing if one assumes there is an ontology (created from classical information) fundamental to that of the classical objects of the block universe. Moving to the 4D perspective allows one to consider an entirely new fundamental ontology, a quantum-classical ontology based on an adynamical global constraint. Indeed, per the Feynman path integral for QM, the most probable path is the classical path and per the transition amplitude for quantum field theory, the most probable field configuration is the classical field configuration [4, Chap. 5].

There seems to be little agreement on what Bohr actually believed, but at least on one possible interpretation of Bohr we are saying the same thing. Namely, that the so-called “quantum system” is in fact the totality of the entire experimental set-up [27, p. 738], such that different set-ups or configurations are not probing some autonomous quantum realm, but actually constitute different “systems.” QM then is a theory that has quantum-classical contextuality at its heart, that is its deepest lesson about the nature of physical reality. As Ball puts it, “the quantum experiment is not probing the phenomenon but is the phenomenon” [28, p. 90]. However, unlike Bohr, given our Lagrangian approach, the entire experimental set-up includes future boundary conditions: the experiment from initiation to termination in 4D spacetime, no Hilbert space required. It goes without saying then that the quantum-classical contextuality we advocate goes beyond the kind of contextuality often associated with the Kochen-Specker theorem. So, that is what the standard formalism per our constraint-based approach has to say about Wigner’s friend. What does the relative-state formalism have to say?

In the Bohmian account (a relative-state formalism) of FR, Lazarovici & Hubert write

the macroscopic quantum measurements performed by [Zeus] and [Wigner] are so invasive that they can change the actual state of the respective laboratory, including the records and memories (brain states) of the experimentalists in it [29].

Per Lazarovici & Hubert, memories and records change, but the history of those memories and records (along their worldlines prior to measurement) remain intact, so nothing in the past is changed. It is exactly analogous to passing vertically polarized light through a polarizer at 45° then measuring it horizontally. The light incident on the first polarizer at 45° has no horizontal component, but it does after passing through the polarizer at 45°. Consequently, it can now pass through the horizontal polarizer. Thus, for the photons that are now passing through the horizontal polarizer, the polarizer at 45° can be said to have changed them from vertically polarized to horizontally polarized. Likewise, Zeus and Wigner’s ẑ and ŷ measurements can literally change Xena and Yvonne’s records and memories of their ˆx and ˆy measurement outcomes.

This does not necessarily constitute scientific contradiction. If Xena and Yvonne’s classical information prior to being measured by Zeus and Wigner is not shared (so that their worldlines are not part of the block universe
of objective reality), and the classical information that exists at the end of the experiment that is shared by all participants is not self-contradictory, then there is no scientific contradiction. Of course, it may be impossible to tell a self-consistent dynamical story about how the initial self-consistent set of classical information evolved into the final self-consistent collection of classical information, but again that is not a problem for adynamical explanation.

Healey also formulates a relative-states approach to FR, which we might infer from his statement

So one could argue that whatever Wigner says about his outcome (more carefully, whatever Zeus measures Wigners outcome to be) is not a reliable guide to Wigner’s actual outcome. In particular, even if Zeus takes Wigner’s outcome to have been OK (because thats what he observes it to be in a hypothetical future measurement on W) Wigner’s actual outcome might equally well have been FAIL. That is, Zeus and Wigner’s outcomes for measurements on Xena and Yvonne’s records can contradict those records [30].

This violates BW and FR’s assumption of consistency only if you subscribe to the belief that QM probabilities apply to an objective reality. Healey and other relative-state approaches simply deny that assumption. Per Healey’s pragmatic account of QM [31], the job of QM is simply to provide the probabilities/correlations for outcomes in a quantum experiment given the experimental context for each observer, i.e., QM is not providing a physical model or interpretation of what happens between experimental initiation and termination – in Bub’s wording, “the non-Boolean link” between the Boolean initial conditions and the Boolean outcomes. Whereas our constraint-based account of QM provides a physical model that includes direct action, Healey’s pragmatic account embraces metaphysical quietism about what happens between the initiation and termination of an experimental set-up. Hence his denial that QM probabilities describe an objective reality.

Assuming the existence of a true quantum system |Ψ⟩ represented by Eq. (14) and the standard formalism, Wigner and Zeus share a common classical context for making their measurements of |Ψ⟩. In the relative-state formalism, Wigner/Zeus must treat Zeus/Wigner as a third quantum system resulting in a new version of Eq. (14) if Zeus/Wigner makes his measurement first. In the standard formalism, Eq. (14) is used by both Zeus and Wigner to determine distributions in their common spacetime context for whatever measurements they decide to make, since their measurements act on different parts of |Ψ⟩ (Zeus on Xena’s lab and Wigner on Yvonne’s lab). Thus, the order of their measurements does not affect the predicted probabilities. For example, per the standard formalism, regardless of what Zeus measures, the probability that Wigner will get an OK outcome for a ˆw measurement if Xena got tails in her ˆx measurement is zero. That is because the tails part of Eq. (14) is

\[
\frac{1}{\sqrt{3}} |\text{tails}⟩|\text{fail}⟩_W
\]

But, in the relative-state formalism, this same probability depends on whether or not Zeus makes his measurement first and what measurement Zeus makes, since the functional form of |Ψ⟩ will be different for Wigner if Zeuss makes an intervening measurement.

For example, suppose Zeus measures ˆx first. After Zeus’s measurement per the relative-state formalism, Eq. (14) reads

\[
|Ψ⟩ = \frac{1}{\sqrt{3}} (|\text{heads}⟩_X|\text{heads}⟩_Z|−⟩ + |\text{tails}⟩_X|\text{tails}⟩_Z|\text{fail}⟩_W)
\]

[Notice we must now distinguish Xena from Zeus even though they are measuring the same thing. The same must be done with Yvonne and Wigner.] In this case, as in the standard formalism, the probability that Wigner will get an OK outcome for a ˆw measurement if Xena got tails in her ˆx measurement is zero because the tails part of Eq. (21) is

\[
\frac{1}{\sqrt{3}} |\text{tails}⟩_X|\text{tails}⟩_Z|\text{fail}⟩_W
\]

after Zeus’s ˆx measurement. But, suppose Zeus makes a ˆz measurement instead. To use the relative-state formalism, we must first cast Eq. (14) in the OK-fail basis as [24]

\[
|Ψ⟩ = \frac{1}{\sqrt{12}} |\text{OK}⟩_X|\text{OK}⟩_Y - \frac{1}{\sqrt{12}} |\text{OK}⟩_X|\text{fail}⟩_Y + \frac{1}{\sqrt{12}} |\text{fail}⟩_X|\text{OK}⟩_Y + \frac{\sqrt{3}}{2} |\text{fail}⟩_X|\text{fail}⟩_Y
\]

Now, after Zeus makes his ˆz measurement, Eq. (23) reads [24]
Thus, the tails part of Eq. (24) is 

$$|\Psi\rangle = \frac{1}{\sqrt{12}} |OK\rangle_x |OK\rangle_y |OK\rangle_z - \frac{1}{\sqrt{12}} |OK\rangle_x |OK\rangle_z |fail\rangle_y + \frac{1}{\sqrt{12}} |fail\rangle_x |fail\rangle_y |OK\rangle_z + \frac{\sqrt{3}}{2} |fail\rangle_x |fail\rangle_z |fail\rangle_y$$

(24)

Thus, the tails part of Eq. (24) is 

$$|tails\rangle_x \left[ \frac{\sqrt{5}}{\sqrt{12}} \left( \frac{3}{\sqrt{10}} |fail\rangle_z + \frac{1}{\sqrt{10}} |OK\rangle_z \right) |fail\rangle_y + \frac{1}{\sqrt{12}} \left( \frac{1}{\sqrt{2}} |fail\rangle_z - \frac{1}{\sqrt{2}} |OK\rangle_z \right) |OK\rangle_y \right]$$

(25)

And since 

$$\left( \frac{1}{\sqrt{2}} |fail\rangle_z - \frac{1}{\sqrt{2}} |OK\rangle_z \right) |OK\rangle_y = |tails\rangle_z |OK\rangle_y$$

(26)

we now have a non-zero probability for Wigner obtaining an OK outcome for a $\hat{w}$ measurement when Xena obtains a tails outcome for her $\hat{x}$ measurement (it is $\frac{1}{6}$ actually [24]). If Zeus does not make a measurement, Eq. (23) becomes 

$$|\Psi\rangle = \frac{1}{\sqrt{12}} |OK\rangle_x |OK\rangle_y |OK\rangle_w - \frac{1}{\sqrt{12}} |OK\rangle_x |fail\rangle_y |fail\rangle_w + \frac{1}{\sqrt{12}} |fail\rangle_x |OK\rangle_w |OK\rangle_y + \frac{\sqrt{3}}{2} |fail\rangle_x |fail\rangle_w |OK\rangle_y$$

(27)

after Wigner’s $\hat{w}$ measurement. The $|OK\rangle_w$ part of this is 

$$\frac{1}{\sqrt{12}} (|OK\rangle_x + |fail\rangle_x) |OK\rangle_y |OK\rangle_w = \frac{1}{\sqrt{6}} |heads\rangle_x |OK\rangle_y |OK\rangle_w$$

(28)

which has no tails piece for Xena, so the probability of Wigner obtaining an OK outcome for a $\hat{w}$ measurement when Zeus has not made a measurement and when Xena obtains a tails outcome for her $\hat{x}$ measurement is again zero.

You can see why Zeus’s intervening $\hat{z}$ measurement per the relative-state formalism can cause possible contradictions between records (as in Healey’s version of the relative-state formalism) or changes to records and memories (as in Lazarovici & Hubert’s version of the relative-state formalism). In the relative-state formalism, Zeus’s measurement outcome must match Xena’s hypothetical or recorded measurement outcome in the basis used by Zeus, e.g., $|OK\rangle_x |OK\rangle_z$. Everything is fine as long as Zeus and Xena make the same measurement, but if Zeus measures in a rotated Hilbert space basis relative to Xena, his possible measurement outcomes will contain cross terms in Xena’s possible measurement outcomes, e.g., $|heads\rangle_x |tails\rangle_z$ and $|tails\rangle_x |heads\rangle_z$, which implies a contradiction between what Zeus measures for Xena’s measurement outcomes and what Xena actually measured and recorded. So that contradiction stands (as in Healey) or Xena’s outcomes change (as in Lazarovici & Huber). Neither of these radical responses is required in our single, self-consistent, 4D block universe model of objective reality.

V. EXPERIMENTAL EVIDENCE FOR NO OBJECTIVE REALITY?

In “Experimental rejection of observer-independence in the quantum world,” Proietti et al. [22] claim to have an experimental result which “lends considerable strength to interpretations of quantum theory already set in an observer-dependent framework and demands for revision of those which are not.” As their depiction of their experiment (Figure 2) clearly shows, all the experimental measurements and outcomes for their experiment occur in a single objective reality, i.e., in the self-consistent, shared classical information of the block universe model of objective reality. And, as they show in their paper, all these outcomes are in accord with QM. Thus, as Carroll notes:

What they have not done is to call into question the existence of an objective reality. Such a reality may or may not exist (I think it does), but experiments that return results compatible with the standard predictions of quantum mechanics cannot possibly overturn it [32].
In Carroll’s take on the experiment per Many-Worlds, Proietti et al. did not cause a branching since

Rather than having an actual human friend who observes the photon polarization – which would inevitably lead to decoherence and branching, because humans are gigantic macroscopic objects who can’t help but interact with the environment around them – the “observer” in this case is just a single photon. For an Everettian, this means that there is still just one branch of the wave function all along. The idea that “the observer sees a definite outcome” is replaced by “one photon becomes entangled with another photon,” which is a perfectly reversible process. Reality, which to an Everettian is isomorphic to a wave function, remains perfectly intact.

Maudlin agrees, saying

The experiments in question are done on a system composed of only six photons. Obviously the photons do not experience anything at all, much less conflicting realities.

And Crowther says

But, on the other hand, the fact remains that these devices are not conscious, and so Wigner could stand resolute in his interpretation. If anything, he could point out that – in the same way that an observation of a non-black, non-raven provides a negligible sliver of confirmation for the claim that ‘all ravens are black’ – the success of the experiment even provides inductive support in favour of his interpretation: the ‘observers’ in this experiment are able to record conflicting facts only because they do not experience these facts.

In other words, Proietti et al. did not in any way screen off a macroscopic measurement device and outcome recording – all measurement devices are visible in Figure 2 and all the experimental outcomes at all times are accessible to all observers in the block universe. Thus, the experiment constitutes a self-consistent (per QM) collection of observations in the 4D block universe model of objective reality. As Lazarovici notes

A group of physicists claims to have found experimental evidence that there are no objective facts observed in quantum experiments. For some reason, they have still chosen to share the observations from their quantum experiment with the outside world.

Maudlin agrees on this point as well, saying

If there is no objective physical world then there is no subject matter for physics, and no resources to account for the outcomes of experiments.

Thus, the Proietti et al. experiment neither establishes the claim in the title of their paper nor provides a true instantiation of the Wigner’s friend experiment. However, we believe their experiment does contain an interesting hint of what we pointed out earlier is otherwise ignored in Wigner’s friend scenarios.

That is, their experiment does hint at what it might mean for Wigner to measure his friend’s lab and measurement results in a rotated Hilbert space basis. Wigner’s non-rotated Hilbert space basis (the direct measurement of Wigner’s
friend’s result) is achieved in Proietti et al. by removing the beam splitter(s) (BS) in Figure 2, thereby measuring \( A_o \) and/or \( B_o \). That means Wigner (here represented by Alice and Bob) is measuring directly both the friend’s “measurement system” (lower exiting red beam on either side) and the friend’s “outcome recording” (upper exiting red beam on either side). Inserting the beam splitter(s) then mixes this information, as represented by a rotated Hilbert space basis.

Of course, in such a case Wigner’s friend’s result would not be in conflict with Wigner’s measurement for two reasons. First, Wigner’s result is a quantum conflated measurement of his friend’s outcome and measurement, so there could be no contradiction in such a result even if there was some way to make sense of the friend’s measurement and outcome when screened off. That is the case in Proietti et al., since the entire experimental set-up exists in the block universe of shared classical information. Second, as we stated earlier, when Wigner’s friend and his lab are screened off from the rest of the universe (contrary to Proietti et al.) there is no common classical context in which to interpret the friend’s measurement and outcome. So, it would be impossible for any contradiction to be observed, i.e., there is no violation of the consistency of shared classical information constituting the block universe.

Simply put, the results that violate Bell’s inequality in the Proietti et al. experiment imply, at worst, that there is no counterfactual definiteness for screened-off quantum systems contributing to the block universe of shared classical information, just as in any other violation of Bell’s inequality. The experiment Proietti et al. should have claimed to instantiate is the quantum liar experiment of Elitzur & Dolev [33, 34].

In the quantum liar experiment, an experimental configuration leads to the creation of a quantum state which then violates the Bell inequality. But, the violation of the Bell inequality by this state denies the very counterfactual definiteness responsible for creating the state to begin with. Again, this does not violate the consistency of shared classical information constituting the block universe model of objective reality [34]. In Proietti et al. the Bell-inequality-violating states represent quantum information about a measurement and its outcome. As with any other combined quantum information, quantum interference can then erase various individual contributions. This interference does not change the friend’s measurement and outcome, it just changes the information concerning the friend’s measurement and outcome, and it does so without jeopardizing the self-consistency of shared classical information constituting the block universe model of objective reality. This is precisely what happened in Proietti et al.

VI. ADYNAMICAL EXPLANATION FOR DELAYED CHOICE QUANTUM ERASER

In addition to Wigner’s friend, another obvious case where there is a possible tension between how we experience the world and some QM experiment is delayed choice quantum eraser. So, in this section, we consider constraint-based explanation for the delayed choice quantum eraser experiment. In order to bring this possible tension out most fully we will alter the set-up of the experiment by adding a conscious agent who attempts to violate the probabilities of QM, as one might think a truly free conscious agent ought to be able to do. Let us start with a description of the experiment.

Using pictures from Hillmer and Kwiat [35], we start with a particle interference pattern (Figure 3) then we scatter photons off the particles after they have passed through the slits(s) (Figure 4) and finally we erase the which-way information obtained by the scattered photons by inserting a lens (Figure 5).

In the Hillmer and Kwiat article the lens (eraser) is inserted after the particles have passed through the slits, but experiments have been done where the ‘lens is inserted’ after the particles have hit the detector. This is called a “delayed choice quantum eraser experiment” [36]. The question from our dynamical perspective is, How do the particles ‘know’ whether or not the lens will be inserted? And, if they do not ‘know’ whether the lens will be inserted or not, how do they ‘know’ whether or not to create the interference pattern? These questions assume temporally sequential, causal explanation, i.e., we are playing chess.

If we rather seek an adynamical, 4D constraint-based block universe explanation in crossword puzzle fashion, we are content with the fact per QM that the distribution of particles on the screen is consistent with the presence or absence of the lens in spacetime. The insertion of the lens does not ‘cause’ the interference pattern any more than the interference pattern ‘causes’ the insertion of the lens. As we stated, no new physics is needed to explain this phenomenon, just the willingness to rise to Wilczek’s challenge.

A recurring theme in natural philosophy is the tension between the God’s-eye view of reality comprehended as a whole and the ant’s-eye view of human consciousness, which senses a succession of events in time. Since the days of Isaac Newton, the ant’s-eye view has dominated fundamental physics. We divide our description of the world into dynamical laws that, paradoxically, exist outside of time according to some, and initial conditions on which those laws act. The dynamical laws do not determine which initial conditions describe reality. That division has been enormously useful and successful pragmatically, but it leaves us far short
Let us now bring the conscious agent into the picture by imagining it is a conscious agent inserting the lens (or not) in the experimental set-up. The question from our dynamical perspective is, What will I experience if I am the agent deciding whether or not to insert the lens? If the predictions of QM are to hold, then my decision must always be in accord with the particle’s behavior at the detection screen and that event occurred before I made the decision. Assuming QM holds, will I feel mentally ‘coerced’ into making the appropriate choice? Will I feel some ‘physical force’ moving my hand against my will?” Most people do not like the idea that our “freely made” decisions can be the result of a single particle striking a distant detector. It would seem that QM does not care about choice at all, delayed or otherwise.

While most people predict that a conscious agent will not violate the probabilities of QM anymore than a classical measuring device, Hardy has proposed an experiment to test this fact. Concerning such an experimental test, he states
FIG. 5. The interference pattern of Figure 3 can be restored after scattering photons as in Figure 4 by destroying the which-way information in the scattered photons (here done by inserting a lens). This is known as “quantum eraser.”

“If” you only saw a violation of quantum theory when you had systems that might be regarded as conscious, humans or other animals, that would certainly be exciting. I can’t imagine a more striking experimental result in physics than that. We’d want to debate as to what that meant. It wouldn’t settle the question, but it would certainly have a strong bearing on the issue of free will.

What explains the agreement between the agent’s decision and the particle’s pattern if it is not “spooky action at a distance” or “backwards causation?” Why does the conscious agent always make the “right” choice in accord with QM? One doubts there is some special new physical or mental force acting on the hand or mind of the conscious observer. For us the answer is simple – we instead ignore our anthropocentric bias and allow for the possibility that objective reality is fundamentally the 4D block universe whose various patterns/distributions are determined fundamentally by adynamical global constraints, not by dynamical laws/processes acting on matter/mind to make it move/decide. We can then accept that there are some constraint-based explanations that do not allow for dynamical counterparts, at least dynamical counterparts without serious baggage, such as those discussed earlier. The constraint-based explanation here is the distribution of quantum energy-momentum exchanges in the block universe context for the experimental set-up and procedure according to the adynamical global constraint of QM, as in section II.

The point is, adynamical global constraints in the block universe also constrain the conscious choices of conscious agents. Thus, physics is already part of psychology in that it places real constraints on what can be experienced to include memories (classical records) and choices. Conscious agents attempting to override QM do not experience any weird forces acting on them because there are no such forces. It is simply the case that their choices will be made in accord with the relevant adynamical global constraints per the reality of the future. Such agents feel like they have Libertarian free will (that the future is open) because they experience reality from the “ant’s-eye” view.

VII. 4D CONSTRAINTS, CONSCIOUS EXPERIENCE AND THE BLOCK UNIVERSE

We have seen that, on our view, the adynamical global (4D) constraints of QM and classical physics are interdependent in accord with quasi-separability (the existence of interacting classical objects). That is, the block universe is the self-consistent collection of shared classical information regarding diachronic entities (classical objects), which interact per QM. The consistency of shared classical information of the block universe is guaranteed by the divergence-free (gauge invariant) nature of the adynamical global constraints for classical and quantum physics. In the case of Wigner’s friend per Healey, the self-consistent collection of classical information would include all shared classical information between Xena, Yvonne, Zeus, and Wigner. In the case of the delayed choice quantum eraser experiment, conscious choices are equally constrained. Here we see a profound connection between QM, relativity, and conscious experience. But, we do not think this is any weirder than the fact that conscious experiences and choices are constrained by other adynamical global constraints, such as conservation laws, the light postulate, and the relativity principle.
Of course as we said there are other interpretations of QM that also uphold the objectivity of experience such as Bohmian mechanics, spontaneous collapse theories and the Many-Worlds interpretation. Again, by ‘objectivity’ we mean what Smolin calls “naive realism,” “according to which what is real consists of events that all observers will universally agree took place” [38, p. 198]. As Smolin notes, recent work about Wigner’s friend aside, there have long been interpretations of QM such as, most recently, Rovelli’s relational interpretation in which all outcomes are relative to “observers.” As with special relativity, observers/reference frames need not be conscious beings, but they include such beings. What would Relational Quantum Mechanics say about Wigner’s friend? “Rovelli would say that it is true, from Sarah’s point of view, that that the cat is alive, and it is also true, from my point of view, that Sarah is entangled in a superposition of ‘seeing dead cat’ and ‘seeing live cat’” [38, p. 196]. Obviously then, here the analogy with various features being relative to reference frames in special relativity (such as simultaneity relations) breaks down. In special relativity naive realism is upheld (even enforced), in Relational Quantum Mechanics it fails to be true, dramatically so.

Let us briefly examine the other interpretations that do uphold objectivity starting with the Many-Worlds interpretation. While it is true that objectivity is strictly speaking upheld, the price is to relativize it to branches of the wavefunction, branches that presumably cannot communicate with one another. So instead of one history wherein “many partial viewpoints define a single universe” [38, p. 197], as with the relational interpretation, you have multiple branches with numerically distinct observers and cats as it were. So on the Many-Worlds interpretation in order to uphold objectivity the universal wavefunction has to split infinitely many times. The universe has objectivity for the simple reason that every QM possibility allowable is actual. Is that really much better? Assuming it is true that Bohmian mechanics and spontaneous collapse theories do not entail branching and granting they do uphold objectivity in the sense that all observers will agree on the outcomes of QM experiments, they do still have a problem that relates to objectivity more broadly. Namely, since they are truly non-local theories with faster than light (space-like) interactions, without invoking a preferred frame, when we insert those interpretations into a relativistic context there will be disagreements about the ordering of events, about which events were causes and which were effects. This strikes us as a pretty profound failure of objectivity as well. For all the problems associated with adding or adopting preferred frames in relativity see Silberstein et al. [4, Chap. 2 & 3]. The bottom line is that our view upholds objectivity in an essential way without any of the baggage of the other interpretations.

How did we get to the point where every decade or two we feel compelled to try and relate the weirdness of the QM wavefunction, such as its alleged collapse, and the weirdness of conscious experience, such as the alleged hard problem and mystery of free will? We got there by making certain assumptions

1. Realism about the wavefunction and Hilbert space.

2. Matter (as described by said wavefunction realism) is fundamental and it is essentially non-conscious, thus the hard problem of explaining “qualia.”

3. Presentism, growing block, or at least the fundamentality of dynamical/causal explanation across the board.

In Silberstein et al. [4], we provide a model of reality that rejects all these assumptions. It is a model of reality not just consistent with our best physics, but driven by our best physics, wherein one need not look to the mystery of QM collapse and the mystery of the hard problem to somehow magically solve one another. Instead of the world as given by these three assumptions, we have one 4D world best described not by physicalism, dualism, panpsychism, or emergentism, but by neutral monism, what William James would call “the field of pure experience.” We cannot do justice to this idea now, but the basic idea of neutral monism is this

Prior to any further categorization, pure experience is, according to James, neutral – neither mental nor material:

The instant field of the present is at all times what I call the ‘pure’ experience. It is only virtually or potentially either object or subject as yet. For the time being, it is plain, unqualified actuality, or existence, a simple that.

Mind and matter, knower and known, thought and thing, representation and represented are then interpreted as resulting from different groupings of pure experience (James 1904b, 23) [39].

Given neutral monism there is no essential difference between what we call matter/physical and what we call experience/mind. That there is such an apparent difference is just a conceptual projection on our part, a conceptual error. If neutral monism is true, then physics and psychology are of course inextricably intertwined, illustrating again that
how we play the game of relating QM to experience is going to depend on a lot of background assumptions about both. Maybe it is time to rethink some of those background assumptions.

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