Zeno Goes to Copenhagen: A Dilemma for Measurement-Collapse Interpretations of Quantum Mechanics*

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Abstract

A familiar interpretation of quantum mechanics (one of a number of views sometimes labeled the "Copenhagen interpretation"), takes its empirical apparatus at face value, holding that the quantum wave function evolves by the Schrödinger equation except on certain occasions of measurement, when it collapses into a new state according to the Born rule. This interpretation is widely rejected, primarily because it faces the measurement problem: "measurement" is too imprecise for use in a fundamental physical theory. We argue that this is a weak objection, as there may be many ways of making "measurement" precise. However, measurement-collapse interpretations face a more serious objection: a dilemma tied to the quantum Zeno effect. Is measurement itself an observable that can enter superpositions? If yes, then the standard measurement-collapse dynamics is ill-defined. If no, then (at least if measurement is an observable), measurements can never start or finish. The best way out is to deny that measurement is an observable, but this leads to strong and revisionary consequences. This reinforces the view that there is no nonrevisionary interpretation of quantum mechanics.

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1 Introduction

A familiar story about quantum mechanics runs as follows. Quantum-mechanical systems can be modeled by a wave function. Most of the time, the wave function evolves according to the deterministic Schrödinger equation. The wave function need not specify definite values for the position, momentum, and other properties of the system. Instead it may specify that the system is in a superposition of many different values for these properties. When one measures these properties, however, one always obtains a definite result. After measurement, the system's wave function is now in a new state that specifies this definite value. The result of the measurement and the resulting wave function are determined probabilistically by the pre-measurement wave function of the system according to the Born rule, which associates wave function amplitudes with probabilities.

The canonical version of this story was given by John von Neumann in *Mathematical Foundations of Quantum Mechanics* (1932/1955). Construed as an empirical apparatus for predicting the results of measurements, this story has been tremendously successful. The predictions made by the story have been borne out again and again, and it has been used to explain all sorts of phenomena. As a result, the empirical apparatus has long ago obtained the status of orthodoxy.

Because of this empirical success, it is natural to construe the story as a description of the reality underlying quantum mechanics. Taken at face value, the story suggests that quantum-mechanical reality is objectively described by a wave function with a bipartite dynamics. First, there is the Schrödinger evolution, which is linear, deterministic, and constantly ongoing. Second, there is a process of collapse into a definite state, which is nonlinear, nondeterministic, and happens only on certain occasions of measurement.

This face-value interpretation of quantum mechanics (Schrödinger equation plus collapse on measurement) is often regarded as a sort of orthodoxy or at least as a starting point for interpreting quantum mechanics, if a starting point that is very frequently rejected. Among physicists this view is often called the "Copenhagen interpretation", associating it with the traditional heft of the Copenhagen school of quantum mechanics led by Niels Bohr and Werner Heisenberg.

Philosophers and historians of science more often use the "Copenhagen" label for Bohr's own quite different interpretation, which was based on his somewhat obscure principle of complementarity and did not invoke collapse.[1] To avoid this ambiguity, we will call the face-value interpretation the *measurement-collapse interpretation*, but we will occasionally allude to the familiar Copenhagen label, for example in our title.[2]

The measurement-collapse interpretation is widely rejected by theorists working in the foundations of quantum mechanics. Perhaps the most common reason for rejection arises from the original "measurement problem": the notion of "measurement" is ill-suited for use in a fundamental theory, as it is imprecise, ill-defined, or anthropocentric (e.g. Bell 1990; Albert 1992). As a result, theorists have focused on revisionary interpretations of quantum mechanics that give no special role to measurement. These include interpretations that give a role to collapse but not to measurement, such as the spontaneous-collapse interpretations developed by G. C. Ghirardi, Rimini, and Weber (1986) and Pearle (1976; 1989). They also include interpretations that dispense with collapse altogether, such as Everett's (1957) many-worlds interpretation and Bohm's (1952) hidden-variable interpretation.

We will argue in section 2 that the standard reason for rejecting measurement-collapse interpretations is a weak one. It is true that the ordinary notion of "measurement" is imprecise. However, as with any imprecise term in physics, we can handle this issue by replacing it by something more precise that plays the same role in our theory. Replacing measurement with a range of different precise notions yields a range of different precise interpretations of quantum mechanics, each of which can be empirically tested in principle.

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[1] The label "Copenhagen interpretation" was introduced by Heisenberg (1955). See Howard (2004) for a history of how Heisenberg's approach differed from Bohr's and led to the contemporary use of the label as standing for the measurement-collapse interpretation. The label is also sometimes used for generic anti-realist views on which the wave function does not describe objective reality and for quietist views in the spirit of "shut up and calculate".

[2] Johnson (2010) suggests that as the two leading proponents of the measurement-collapse interpretation, von Neumann and Eugene Wigner, were both Hungarian, it should be called the "Budapest interpretation". If that convention were adopted, this article might then be called "Zeno Goes to Budapest".

However, measurement-collapse interpretations face a more serious objection that (as far as we know) has not been noted previously. This objection arises from the quantum Zeno effect, which tells us that when we continuously measure an observable in a system, the value of that observable will never change. The source of the quantum Zeno effect is the mathematical fact that for a system to evolve from one eigenstate (definite state) of an observable into another by Schrödinger evolution, it must always pass through superpositions of these eigenstates. Continuous measurement of an observable prevents these superpositions from arising, so prevents change between eigenstates.

The quantum Zeno effect was first described by Alan Turing (Gandy 1954), and was mathematically derived by Degasperis, Fonda, and G. Ghirardi (1974). Misra and Sudarshan (1977) called it “a Zeno’s paradox for quantum theory”. They regarded it as raising a genuine paradox for standard quantum mechanics, on the grounds that we never observe the predicted freezing of quantum systems on continuous measurement. In a similar vein, Ballentine (1998, p.343) says that measurement-collapse interpretations are “disproven by the simple empirical fact that continuous observation does not prevent motion”.

In the ensuing years, most researchers have come to regard the Zeno phenomenon as non-paradoxical, for a number of reasons. First, weaker versions of the phenomenon involving slowing rather than freezing have been demonstrated experimentally (Itano et al. 1990). Second, it has been argued that the strong continuous measurements required for freezing are either practically or theoretically impossible (Nakazato et al. 1995). Third, it has been shown that a version of the Zeno effect follows from the Schrödinger equation alone, with or without the collapse postulate (Pascazio and Namiki 1994). As a result, the Zeno effect is widely held to be consistent both with empirical evidence and with all of the major interpretations of quantum mechanics.

We will argue that nevertheless, reasoning based on the Zeno effect raises a serious difficulty for measurement-collapse interpretations of quantum mechanics. This difficulty is quite distinct from the Misra-Sudarshan “paradox” and is not dissolved by the considerations mentioned above. Where the Misra-Sudarshan “paradox” concerns the potential freezing of observables that are measured, the dilemma we are raising concerns the potential freezing of measurement itself.

To raise the problem, we can ask: can measurement itself enter superpositions? For example, can a particle be in a superposition of having its position measured and not having it measured? If it can, the standard dynamics is ill-defined, since the standard dynamics requires that collapse either happens or it does not, depending on whether measurement occurs. If it cannot, then the Zeno effect tells us that at least if measurement is itself a quantum observable, measurement states can never change, so that nothing can be measured after not being measured. Either way, the standard dynamics is not correct. In section 3, we will set out this dilemma more carefully. In sections 4-6 we look at the main options for escaping it, which require denying that measurement is a quantum observable.

Our conclusion is that endorsing a measurement-collapse interpretation requires some fairly radical revisions or additions to standard quantum mechanics. It requires either a strong form of dualism or treating measurement non-standardly as a special wave-function property. This does not entail that no measurement-collapse interpretation is correct, but brings out the costs of such an interpretation more clearly. It also brings out that insofar as measurement-collapse provides the orthodox empirical apparatus for quantum mechanics, any tenable interpretation of quantum mechanics must be somewhat revisionary.

2 The measurement problem for measurement-collapse interpretations

The standard objection to measurement-collapse interpretations is a version of the *measurement problem*: the notion of measurement is ill-suited for use in a fundamental theory, as it is imprecise, ill-defined, or anthropocentric.

To illustrate the problem, we can ask questions such as: Does a rock make measurements? A camera? An ant? A cat? The ordinary notion of measurement leaves the issue unclear or ill-defined, and thereby leaves the measurement-collapse dynamics of quantum mechanics unclear or ill-defined. Sometimes measurement is restricted to humans, which may yield a little more precision, but there is still some imprecision (for example, does unconscious perception count as measurement?). There is also now an issue of anthropocentrism: it is unclear why the fundamental physical dynamics of the world should give such a special role to humans. So at least with ordinary notions of measurement, the measurement-collapse dynamics seems to be imprecise and possibly anthropocentric as well.

We think the standard objection is a weak one. As with other imprecise notions used in physics, we can handle this issue by replacing it with something more precise: in particular, a precise mathematical criterion for when a given observable is measured. For example, Tononi (2008) has given a precise mathematical measure ϕ of information-integration in a system. We could define measurement so that only systems with ϕ above a certain precise threshold are measuring devices and an observable in another system is measured only when it becomes entangled with ϕ in the measuring system. This is just one example. There are an infinite number of other ways of making measurement precise.

In effect, the imprecise measurement-collapse interpretation can be seen as a template for a large number of more precise interpretations where "measurement" is replaced by some precise criterion for collapse. None of these interpretations are ill-defined or imprecise. Some of them may be anthropocentric, but many are not. If there is a problem in the vicinity, it is that many different precise interpretations are available, and we do not know which of them is correct. But this is not really an objection to these interpretations. It is simply an invitation to further investigation.

Importantly, these precise measurement-collapse interpretations can all be empirically distinguished from each other. Different hypotheses about the locus of collapse make different predictions about where and when quantum superpositions and resulting quantum interference effects will be found, and these predictions can be tested by experiments using interferometers and the like. Many of these experiments are not yet practically possible, but they are possible in principle. So there is at least an in-principle empirical research program of testing the many precise measurement-collapse interpretations to see which if any may be correct. The "imprecision" in the central notion of measurement simply amounts to a degree of freedom in our theories that is subject to empirical inquiry.

On one common understanding of measurement, it is equivalent to conscious observation. Given this understanding of measurement, the measurement-collapse interpretation leads to the *consciousness-collapse* interpretation (put forward by Wigner 1961), on which consciousness collapses the wave-function. However it is also possible to understand measurement quite independently of consciousness, in which case a measurement-collapse interpretation need give no special role to consciousness. In this paper we are focusing on the broader class of measurement-collapse interpretations without assuming a connection to consciousness, but we will attend to consciousness-involving interpretations on occasion.

In formal terms, how can we understand measurement? Here is a fairly standard statement of the collapse postulate in quantum mechanics:

> Carrying out a "measurement" of an observable B on a system in a state $|A\rangle$ has the effect of collapsing the system into a B-eigenstate corresponding to the eigenvalue observed. Which particular B-eigenstate it collapses into is a matter of probability, and the probabilities are given by a rule known as Born's Rule: $prob(b_i) = |\langle A|B = b_i\rangle|^2$. (Ismael 2015, Stanford Encyclopedia of Philosophy)

Here, the role played by measurement in the dynamics is that when an observable O of a system S is measured, S collapses into an eigenstate of O, with probabilities determined by the Born rule. We can think of measurement as a two-place property m of (system, observable) pairs. Here $m(S, O)$ obtains when the observable O is being measured in system S. For example, when the x-spin of a particle e is measured, $m(e, x\text{-spin})$ obtains.

The collapse postulate tells us that when $m(S, O)$ obtains, the wave function of S collapses onto an eigenstate of O according to the Born probabilities. As long as m is a precise property of (system, observable) pairs, the resulting dynamics will be precise and well-defined, at least setting aside worries arising from relativity (which requires an extensive treatment of its own) and from simultaneous measurement (where constraints will be needed in order to prevent simultaneous measurement of incompatible observables such as position and momentum).

On a traditional conception of measurement, one can think of the two-place relation $m(S, O)$ as deriving from a three-place relation $M(S', S, O)$ which holds when a (measuring) system S' is measuring observable O in a (measured) system S. On this conception, $m(S, O)$ obtains iff there exists a system S' such that $M(S', S, O)$ obtains. However, for our purposes there is no need to explicitly invoke the measuring system S' or the three-place relation M. We can obtain a simpler and more general treatment by staying with the two-place relation $m(S, O)$. That said, readers should feel free to think in terms of measuring systems by translating $m(S, O)$ into $\exists S' M(S', S, O)$).

In fact, the argument that follows does not require understanding m in terms of measurement or observation at all. In principle any precise property m of (system, observable) pairs meeting the constraints mentioned above can serve as a trigger for collapse. There will be a different precise collapse dynamics for every choice of an underlying property m, so a wide range of precise interpretations is available. We might think of these interpretations as *triggered-collapse* interpretations, on which there is a trigger for collapse that may or may not involve measurement. (These contrast with spontaneous collapse interpretations, on which collapse occurs without a trigger.) We will focus on measurement-collapse interpretations in what follows, but the analysis applies to triggered-collapse interpretations more generally.[3]

The original objections to measurement-collapse interpretations— that measurement is imprecise, ill-defined, or anthropocentric—do little to threaten an interpretation involving a precise property m. The residue of the first two

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[3] Taxonomy: As we understand them, spontaneous-collapse and triggered-collapse interpretations are both objective-collapse interpretations, on which collapse happens in objective reality. Triggered-collapse interpretations include measurement-collapse interpretations as a proper subset, and also include views on which the trigger has nothing to do with measurement (such as Penrose's interpretation discussed later in the paper). Measurement-collapse interpretations include consciousness-collapse interpretations as a proper subset, and also include views on which measurement has nothing to do with consciousness (such as the view von Neumann entertains on which measurement takes place in ordinary measuring devices). There can be some argument over cases: for example, does GRW count as a triggered-collapse interpretation because the size of a system serves as a trigger?

charges is perhaps an objection from evidence: we do not have specific evidence that any of these specific interpretations is correct. But this is true of most interpretations of quantum mechanics, and it provides little reason to reject the theories. The residue of the third charge is perhaps an objection from complexity: m is almost certainly a complex property of physical systems, and other physical theories do not give a fundamental role to complex properties. It is true that this would make quantum mechanics unlike other physical theories to date, but it is unclear that there is any reason in principle that complex properties cannot play a role in fundamental physical dynamics.

There are also a few well-known problems for all collapse interpretations that apply to the measurement-collapse interpretations. These include the problem of consistency with relativity (Maudlin 2011) and the "tails" problem (McQueen 2015). These problems have not prevented spontaneous-collapse interpretations from being taken seriously, however, and the problems are not obviously any worse where measurement-collapse interpretations are concerned. For present purposes we will set those problems aside to focus on a problem that is distinctive to the measurement-collapse view.

3 The Zeno dilemma

We can set things up for the Zeno Dilemma by asking: can measurement be measured? Or more precisely: is there a quantum observable corresponding to $m(S, O)$? On the face of it, one would expect that there might be. On most understandings of measurement we can certainly observe one system measuring another, so if we understand m in terms of measurement one would expect it to be an observable. In quantum mechanics, the key class of quantum observables are quasi-classical properties of classical basis states, corresponding to Hermitian operators. On many natural ways of understanding measurement, it will be a quasi-classical property of this sort.

To convert the relation $m(S, O)$ into an observable, we need to define a numerical quantity $m_{S,O}$:

$m_{S,O} = 1$ if $m(S, O)$ obtains (i.e. if O is measured in S);

$m_{S,O} = -1$ if $m(S,O)$ does not obtain (i.e. if O is not measured in S).

If this quantity $m_{S,O}$ is an observable, there will be an associated Hermitian operator whose eigenstates are $|m_{S,O} = 1\rangle$ and $|m_{S,O} = -1\rangle$.

The measurement of observables in system S may depend on what is going on outside S, perhaps in a separate measuring system S'. If so, $m_{S,O}$ will not itself be an observable of S, as observables of S depend only on S and not on matters external to S. Instead, $m_{S,O}$ will be an observable of a broader system, such as a combined system $S + S'$ or the universe as a whole.

For now, we will assume that $m_{S,O}$ is an observable to see what follows. Later we will consider the alternatives.

Assuming that $m_{S,O}$ is an observable, we can then pose the Zeno dilemma by asking: is $m_{S,O}$ open to quantum superposition? That is, can systems enter superpositions of eigenstates of $m_{S,O}$? For example, can an electron e and its position p fail to have a definite value of $m_{e,p}$, with the system instead being in a superposition of $|m_{e,p} = -1\rangle$ and $|m_{e,p} = 1\rangle$? Or put in terms of measurement: can a particle be in a superposition of the state of having its position measured and the state of not having its position measured?

If the answer is yes: then the standard measurement-collapse dynamics is ill-defined. The standard dynamics tell us that if $m(S,O)$ obtains, S collapses onto an eigenstate of O, and if $m(S,O)$ does not obtain, S does not collapse. When S is in a superposition of $m_{S,O}$, there is no fact of the matter about whether or not $m(S,O)$ obtains, and so the standard dynamics do not specify any fact of the matter about whether S collapses. The dynamics says nothing about what happens when the world is in a superposition of $m_{S,O}$, or when the system is in a superposition of being measured and not being measured. Perhaps one could suggest that the wave function undergoes a superposition of collapsing and not collapsing, but a moment's reflection reveals that this does not really make sense. Perhaps one could suggest that collapse requires an eigenstate of $m_{S,O}$, so that superpositions of $m_{S,O}$ never trigger collapse, but now there is the threat that the wave function will never collapse again. In any case, all of these options require going well beyond the standard dynamics, which assume that being measured or not is a binary and determinate matter.

If the answer is no: then $m_{S,O}$ can never change its value, so that a system can never come to collapse after not collapsing.[4] This reflects the quantum Zeno effect, which is often glossed as saying that when a quantum observable is continuously measured, its value can never change. If an observable is continuously measured, the measured system will always be in an eigenstate of that observable. The mathematics of Schrödinger evolution entails that a system cannot evolve from being in one eigenstate of an observable to another eigenstate without going through a non-eigenstate of that observable. So if systems can never enter superpositions of $m_{S,O}$ eigenstates, $m_{S,O}$ can never change under Schrödinger evolution. As a result, Schrödinger evolution can never lead from a state where the wave function does not collapse to a state where the wave function collapses, and the measurement-collapse dynamics will fail.

In effect, if $m_{S,O}$ can never enter superpositions, it is as if $m_{S,O}$ itself were constantly being measured, so that $m_{S,O}$ always keeps a definite value whenever it would otherwise enter a superposition. The quantum Zeno effect tells us that in a case of "strong continuous measurement" like this, the continuously measured observable can never change precisely because it can never enter a superposition.

One can turn the Zeno problem into a inconsistent tetrad for measurement-collapse interpretations. Here $m_{S,O}$ as before is the condition under which collapse occurs: a system collapses into an eigenstate of O iff $m_{S,O} = 1$. We will say that an observable is *superposable* if it is possible for a system to enter a superposition of eigenstates of that observable. We will say that an observable is *changeable* if a system can have one value of that observable at one time and another value at a different time.

(1) $m_{S,O}$ is an observable.

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[4] If $m(S,O)$ is an observable that cannot enter superpositions, it is as if there is a superselection rule forbidding superpositions of $m(S,O)$. Thalos (1998) argues that superselection rules cannot explain the measurement processes, in large part on the grounds that superselected quantities cannot change over time. Her critique is not directed at measurement-collapse interpretations and does not discuss superpositions of measurement per se, but the current point can be seen as an application of Thalos's analysis to certain measurement-collapse views.

(2) $m_{S,O}$ is not superposable.

(3) $m_{S,O}$ is changeable.

(4) If an observable is not superposable, it is not changeable.

These four claims are clearly inconsistent. Which should a proponent of the measurement-collapse interpretation reject? We will work through them in reverse order.

(4) is a mathematical property of quantum mechanics under Schrödinger evolution and collapse. One might suggest that a non-superposable observable could be changeable via collapse rather than via Schrödinger evolution, perhaps by measuring a different observable. However, this would require that a system in an eigenstate of $m_{S,O}$ collapses directly into a different eigenstate of the same observable, which is mathematically impossible. Measuring observable O_2 of a system in an eigenstate of an observable O_1 always leads either to the same eigenstate (if the two observables commute) or to a non-eigenstate of O_1 (if they do not).

Someone might suggest that violations of (4) for measurement are built into the special dynamics of measurement and collapse. For example, perhaps at the instant of measurement and collapse, measuring systems transit directly from a non-measurement eigenstate to a measurement eigenstate (e.g. from a "ready" eigenstate to an eigenstate in which a measurement result is recorded). This special dynamics will go beyond the standard wave-function dynamics of Schrödinger evolution and collapse. On one version of the picture, measurement is autonomous from the underlying wave-function so that it can vary independently. That version leads to the dualist picture discussed in section 5. On another version of the picture, measurement depends on the underlying wavefunction so that the wavefunction of a measuring device will jump directly between eigenstates. This will require new wave-function dynamics that will take some spelling out.[5]

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[5] One common way to represent the measurement process (e.g. Albert 1992, ch.4) involves a measurement device d measuring an electron e transitioning from a "ready" eigenstate to an eigenstate displaying a result as follows: $|ready\rangle_{\mathrm{d}}\,|{\uparrow_z}\rangle_{\mathrm{e}} \rightarrow |up_z\rangle_{\mathrm{d}}\,|{\uparrow_z}\rangle_{\mathrm{e}}$. This presentation may make it seem that the device d evolves directly from the ready state to the collapse state

It is very hard to deny (3), which says that $m_{S,O}$ is changeable. On any measurement-collapse interpretation there will be systems that undergo collapse when certain observables are measured, and this collapse will happen at certain times and not at other times. Given that an observable O of system S collapses depending on the value of $m_{S,O}$, this requires that at least for some S and O, $m_{S,O}$ sometimes changes its value.

Denying (2) may seem somewhat more attractive. The worry was that if $m_{S,O}$ is superposable, the dynamics will not be well-defined, but there are various options for fleshing out the dynamics here. Perhaps the most natural suggestion is that only eigenstates of $m_{S,O}$ trigger collapse. That is, system S collapses onto an eigenstate of O only when the overall system is in the eigenstate $|m_{S,O} = 1\rangle$. Superpositions of $|m_{S,O} = -1\rangle$ and $|m_{S,O} = 1\rangle$ are possible, but these superpositions never trigger collapse. This now provides a well-defined criterion for measurement.

For this view to work and to avoid the Zeno dilemma in ordinary measurement situations, superpositions of $m_{S,O}$ eigenstates must evolve by Schrödinger evolution into eigenstates $|m_{S,O} = 1\rangle$ which will then trigger collapse. The obvious worry is that there is little reason to think that superpositions will always evolve into eigenstates as required. In a typical case, we would expect superpositions of $m_{S,O}$ eigenstates to lead to more superpositions and eventually to decoherent components of the wave function in which the measurement activity in different components is quite different. On this picture there is little reason to expect that ordinary measurement situations will lead to definite measurement outcomes.

On an alternative picture that denies (2), only certain sorts of superposition of $m_{S,O}$ eigenstates trigger collapse. For example, perhaps collapse takes place only on a sufficiently large superposition, or only with a sufficiently decoherent

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without any problem. However, the problem arises with the transition. In accord with the collapse postulate electron e has already collapsed to $|{\uparrow_z}\rangle_{\mathrm{e}}$. The collapsed electron then causes the device to enter the state $|up_z\rangle_{\mathrm{d}}$, as in the transition above. Since the collapse postulate has done its job already, the transition must be achieved by the Schrödinger dynamics. Since $|ready\rangle_{\mathrm{d}} |{\uparrow_z}\rangle_{\mathrm{e}}$ and $|up_z\rangle_{\mathrm{d}} |{\uparrow_z}\rangle_{\mathrm{e}}$ are orthogonal eigenstates, the Schrödinger dynamics must transition through intermediate superpositions of these eigenstates in order for this transition to occur.

wave-function. In effect, this is to say that collapse is triggered by an elaborated condition $m'_{S,O}$ as a property that a system has when it is in a certain sort of superposition of $m_{S,O}$ eigenstates, where $m'_{S,O}$ is a property of a wave function as a whole. However, we can now apply the quadrilemma above to m'. In this version of the quadrilemma, we will deny (1) for the new property m', as it is a wave-function property rather than a quantum observable (as discussed later). So this move does not really open up new space for resisting the quadrilemma. It is in effect equivalent to denying (1) for the triggering property, an important move that we will discuss shortly.

A third suggestion is that the measurement-collapse process may have an extended dynamics and that $m_{S,O}$ may be superposable during the post-measurement period. For a very simple example: perhaps a definite value of $m_{S,O}$ is required to trigger collapse, but then collapse takes place one second later. A nonstandard post-measurement dynamics like this may help explain how measurement can be followed by non-measurement (the overall system is in $|m_{S,O} = 1\rangle$, this triggers collapse, the system enters a superposition of $|m_{S,O} = 1\rangle$ and $|m_{S,O} = -1\rangle$ and then collapses onto $|m_{S,O} = -1\rangle$. However, post-measurement dynamics does nothing to explain the crucial case in which non-measurement (ordinary Schrödinger evolution without measurement or collapse) is followed by measurement. Explaining the onset of measurement requires something quite different.

Relatedly, one might consider departing from the standard Copenhagen dynamics by allowing collapse to be triggered stochastically. For example, $m_{S,O}$ may be a quantitative property yielding a rate or degree of collapse. This approach is subject to the same sort of dilemma—can $m_{S,O}$ and the associated rate or degree enter superpositions? Whether yes or no, the same issues arise. So this option does not really open new ground in dealing with the dilemma.

The remaining and best option is to deny (1), embracing interpretations on which measurement is not an observable and is therefore not subject to superposition and the Zeno effect. There are three fairly natural ways to do this.

First, we could say that measurement is a *classical* property. It is often held that classical properties are distinct from quantum observables and are not subject to the same principles. If so, measurement may not be subject to the quantum Zeno effect, and the dilemma might be evaded.

Second, we could say that measurement is a *nonphysical* property. The most natural way to do this is to endorse a mind/body dualism on which mental properties and physical properties are fundamentally distinct, and hold that measurement involves a mental property which is not subject to quantum-mechanical principles.

Third, we could say that measurement is a *wave-function property.* This is a property of a quantum system that is determined by its whole wave function and which does not enter quantum superpositions. For example, the property of having a position superposed with a certain degree of spread is a wave-function property of a particle. This property is not a quantum observable and does not itself enter superpositions. It nevertheless can straightforwardly change and is not subject to the Zeno effect. If measurement is a wave-function property, the dilemma might be avoided.

There are various other ways that measurement could fail to be an observable, but they seem less promising for resisting the dilemma. Measurement could depend on a combination of noncommuting observables (such as position and momentum) so that it is not itself an observable, or it could depend on the state of a system across time. In these cases, the dilemma rearises for the underlying observables (at a time or across time) on which measurement depends: if these components cannot be superposed, they cannot change, and if they can, the dynamics is ill-defined. Measurement could also be a quantity such as entropy that is defined only relative to the knowledge of an observer, but then measurement will not give an objective criterion for collapse.

We will investigate each of the three main options (measurement as a classical property, a nonphysical property, or a wave-function property) in the following sections.

4 Measurement as a classical property

The first option is to say that measurement is a classical property that is not governed by quantum principles such as the quantum Zeno effect. A picture like this is suggested by some of Bohr's and Heisenberg's philosophical remarks about quantum mechanics, which stress that the classical realm is different in kind from the quantum realm and is subject to different principles. In particular, Bohr and Heisenberg stress that we need to treat an experimental apparatus as a classical system while treating the systems measured by the apparatus as a quantum system. On this picture, it is natural to treat measurement as a classical process that is not itself subject to quantum principles.

An extreme version of this option is *quantum/classical dualism*, which says that there are distinct and separate quantum and classical realms, neither of which is derivative from the other. On this view, fundamental reality involves both quantum entities and properties, governed by quantum dynamics, and classical entities and properties, governed by classical dynamics. But this is not at all the picture given by quantum physics. Quantum physics tells us that fundamental physics is entirely driven by quantum principles, and classical principles have no place at the fundamental level.

A more common picture of the quantum/classical divide is that the "classical" realm emerges derivatively and gradually from the quantum realm. It is widely held that this emergence of classical processes involves a process of decoherence, in which Schrödinger evolution leads quasi-classical branches of the wave function to become largely independent of each other. On a collapse interpretation, the emergence of classical processes will also centrally involve collapse, whereby one of these decoherent branches is selected as actual. This picture does not require a quantum/classical distinction at the fundamental level.

One might use this picture of emergent classicality to respond to the Zeno dilemma. In particular, it may be suggested that measurement devices lie at the classical level and so are not subject to quantum dynamics such as the Zeno effect. An opponent might note that the Zeno effect does not seem to apply to macroscopic systems. One can continuously observe a moving car without the car freezing, for example. If so, one would expect that in macroscopic systems, measurements could also start and stop without freezing.

This response is tempting, but it is incorrect. The Zeno effect, understood as the claim that in order for a system to change between definite states of an observable, it must enter a superposition, is a mathematical property of quantum mechanics (under Schrödinger evolution with or without collapse) and applies equally to microscopic and macroscopic systems. Furthermore, the position of a macroscopic object can be regarded as a quantum observable. It is a property of a classical basis state that can in principle be measured and corresponds to a Hermitian operator. Of course the position of a macroscopic object derives from positions and mass densities of simpler objects, so it is not a fundamental observable, but it is no less an observable for all this than the position of a molecule. Correspondingly, macroscopic objects can enter superpositions of position eigenstates. On an Everett-style interpretation of quantum mechanics, the position of a macroscopic object may enter large superpositions. And even on a collapse interpretation of quantum mechanics, the position of a macroscopic object must enter at least small superpositions in order to change. Of course these superpositions will not typically be macroscopically detectable, but they will always be present.

Consequently, *if* we carried out a strong continuous measurement of the position of a macroscopic object so that the position could never enter a superposition, then the macroscopic object would never change its position. As discussed earlier, we never observe this effect, for the familiar reason that strong continuous measurements are difficult or impossible to perform. The same is true even at the microscopic level, where one never sees the extreme case of the Zeno effect when measuring the position of a particle, because we cannot perform strong continuous measurements. It remains a mathematical fact that for microscopic or macroscopic position to be changeable, it must be superposable.

In the case of measurement, by contrast, we have stipulated (at least on the relevant horn of the dilemma) that measurement is non-superposable. As a result, measurement is unlike ordinary macroscopic properties which are superposable and which change only through superpositions. Instead measurement is constrained to evolve exactly as if measurement was itself being strongly continuously measured, at least if measurement is an observable. It follows that measurement cannot start and stop. Furthermore, given that "classical" macroscopic properties such as position are still quantum observables, it is incorrect to say that measurement is not a quantum observable because it is classical. Perhaps there is some other quite different reason to deny that measurement is a quantum observable, but this leads us to the options covered in the next two sections.

5 Measurement as a nonphysical property

The second option holds that measurement is a nonphysical property. On the most natural version of this view, measurement is a mental property which is distinct from any physical property and is not itself governed by quantum principles.

This sort of mind/body dualism is familiar in the quantum-mechanical context. Wigner (1961) appealed to mind/body dualism in his famous argument that consciousness collapses the wave function. Precisely what made consciousness suitable for this role, on his view, was that it is nonphysical and therefore not governed by the usual quantum principles of superposition and Schrödinger evolution. In recent years, a dualist consciousness-collapse interpretations has been developed further by Henry Stapp (1993), who holds that measurement is an act of consciousness involving a free choice of what to measure.

Mind/body dualism is a familiar philosophical view which has some supporters. But to make a measurement-collapse view work, we need a very strong form of mind/body dualism on which the mind is strongly independent of the body. Descartes endorsed a strong form of substance dualism, on which the mind is a Cartesian ego that can exist independently of the body and whose state does not depend only on the state of the brain. By contrast, the forms of mind/body dualism that have been most widely discussed in recent years involve a sort of naturalistic property dualism, with mental properties that depend systematically on physical properties according to strict psychophysical laws. Naturalistic property dualism is better behaved than Cartesian substance dualism, but it makes it much harder to avoid the Zeno dilemma.

On a naturalistic property dualist view, there are systematic physical correlates of consciousness. On an especially well-behaved version of this view, for every state of consciousness C, there is a corresponding physical state P such that one is in C if and only if one is in P. For example, one may experience a pointer in one position if and only if one's brain is in state P1, while one may experience a pointer in another position if and only one's brain is in state P2. There are also weaker versions where physical states correspond many-one to states of consciousness, but these end up raising the same issues.

Unfortunately, using standard property dualism with physical correlates of consciousness to ground a measurement-collapse view leads straight back to the Zeno problem. Presumably we will say that wave function collapse will be triggered iff one is in a certain state C of consciousness (or perhaps a more complex state involving consciousness, but the issues will be the same). On the naturalistic property dualist view, one will be in state C iff one is in physical state P. We can now ask: can P enter a superposition? For example, can one's brain be in a superposition of states corresponding to P and not-P?

If P cannot enter a superposition, we are subject to the Zeno problem. P can never change, and so C can never change either. So one can never move from lacking the relevant state of consciousness to having it, and a measurement process can never begin.

If P can enter a superposition, then it is unclear that the measurement dynamics are well-defined. It is most natural to say that if one is in a superposition of P and not-P, then one's consciousness will be in a superposition of C and not-C. It is not obvious what it means to say that consciousness is in a superposition, but even if we can make sense of this, the dynamics are unclear in a familiar way. The original dynamics said that state C triggers collapse while not-C does not. On the face of it a superposition of the two will lead to a superposition of collapse and noncollapse, which does not make sense. To avoid the problem, something more is needed.

One could perhaps embrace a form of property dualism where the physical correlates of consciousness are wave-function properties. For example, perhaps one is in a conscious measurement state if and only if one's brain is in a certain sort of superposition. This would avoid the Zeno dilemma in much the same way as taking measurement to be a wave-function property avoids the dilemma. This strategy requires an unusual theory of consciousness, however, and it also requires an appeal to wave-function properties as a trigger of collapse. As a result, it is not entirely distinct from the third option discussed below and it raises similar issues.

To avoid the Zeno problem without an appeal to the second option, one needs a strong form of dualism on which consciousness does not straightforwardly depend on states of the brain. It is worth noting that the same analysis applies to quantum/classical dualism. To avoid the Zeno problem entirely via quantum/classical dualism, one needs a strong dualism where classical states do not straightforwardly depend on quantum states.

If we adopt a strong form of mind/body dualism, there will be no perfect physical correlates of consciousness, and consciousness will be somewhat autonomous from the brain. A view like this can allow that consciousness is always in a definite state even when the brain is in a superposition. Presumably entering certain states of conscousness will trigger a collapse in one's brain and in states of the world that are entangled with it.

This view avoids the Zeno problem, but it still raises many puzzles. For a start, it is quite unclear what the autonomous dynamics of consciousness will be once it does not depend entirely on physical dynamics. Stapp's version of the view requires consciousness to make free choices of which properties to measure, but he gives no account of this dynamics (which he calls "process 0") and instead takes it as primitive.

A relative of the Zeno problem may also still arise from causal connections between states of the visual cortex (say) and states of consciousness. Presumably the visual cortex is sometimes in a superposition of two states (representing an object in location A and location B, say), which gives rise to a definite conscious state (perceiving the object in location A, say) which leads to a collapse in visual cortex and the rest of the brain. But now there is a danger that the immediate physical antecedents of consciousness will themselves be subject to the Zeno effect, as was the case for physical correlates of consciousness earlier. Perhaps there will be a small delay that allows these antecedents to enter brief superpositions and avoid the Zeno effect, but it will at least be a challenge to develop a dynamics that avoids the problem entirely.

Perhaps these problems can be solved, but it is clear that a very strong form of mind/body dualism is required. The standard quantum dynamics will be quite incomplete as an account of the dynamics of reality, and we will need a separate mental dynamics. So on this view the standard Copenhagen interpretation will at best be incomplete.

6 Measurement as a wave-function property

The final option for avoiding the Zeno dilemma is to treat measurement as a wave-function property. That is, the trigger of collapse is not an observable that can enter superpositions, but rather is a property of a quantum wave function as a whole.

For example, wave functions have many binary properties at times. They have certain patterns of amplitude, or they do not. They involve certain sorts of superpositions, or they do not. Wave functions also have many degreed properties at times. For example, a particle's wave function for position can involve greater or smaller degrees of superposition. The binary and degreed properties are not themselves subject to superposition. A system cannot be in a superposition of having a wave function with a certain amplitude distribution and not having such a wave function, or of having a large and a small degree of superposition.

As a result, treating measurement as a wave-function property has the potential to avoid the Zeno problem. It can always be a definite matter whether a measurement is taking place, and a wave function can evolve straightforwardly from a non-measurement state to a measurement state.

The hard questions for such a view are: just which wave-function property triggers collapse, and how exactly does the collapse process work? Certainly there is no suggestion in standard quantum mechanics that measurement is a special wave-function property, and intuitively we tend to think of measurement as a paradigm of a quasi-classical process. So here we need to go beyond standard methods of thinking about quantum mechanics.

There are perhaps two especially natural approaches to understanding the trigger for collapse as a wave-function property. On one approach, collapse is triggered by *decoherence*. When a wave function enters a sufficiently decoherent state relative to some basis, on which it is a superposition of largely non-interfering quasi-classical alternatives, the wave function collapses onto one of those alternatives. An observable of a system collapses when it becomes part of a decoherent quantum system. This *decoherence-collapse* interpretation has the promise of combining some of the virtues of interpretations involving decoherence and those involving collapse, but we set it aside here.

On the second approach, collapse is triggered by *superposition*. In particular, it is triggered by a sufficiently great degree of superposition of certain key observables.

The most well-known proposal along these lines has been made by Roger Penrose (2014). Penrose holds that collapse is triggered when spacetime enters into certain superpositions involving sufficiently different structures. Here, the trigger for collapse is a wave-function property: a certain degree of superposition of spacetime structure. The collapse process itself is stochastic: greater degrees of superposition lead to higher probabilities of collapse. Penrose does not identify this wave-function property with measurement, and intuitively superpositions of spacetime can take place without anything we ordinarily think of as measurement. But one could also apply his approach to other triggers for collapse that are more linked to standard measurement.

A generalization of this approach by Chalmers and McQueen (forthcoming) holds that there is a special class of *superposition-resistant* observables associated with measurement (akin to pointer positions or perhaps states of a perceptual system) that are responsible for collapse. On a simple version of this approach, superposition-resistant observables can never be superposed, which leads to the Zeno problem. To avoid the problem, we can instead say that superpositions of these observables are unstable, so that large enough superpositions trigger a collapse toward an eigenstate of the observable with high probability. This will then also collapse any external systems that are entangled with the superposition-resistant observable.

This approach is somewhat revisionary insofar as it involves a fixed locus for collapse, whereas the standard measurement-collapse dynamics allow a variable locus of collapse (any observable can serve as the primary locus of collapse, if it is measured). In effect, on this framework $m_{S,O} = 1$ only when O is a special superposition-resistant property. We could perhaps define an extended notion of measurement that applies to any observable, so that O is measured iff it becomes entangled with a superposition-resistant observable, but the fundamental locus of collapse is still the superposition-resistant observable and not O.

Other nonstandard pictures have been developed with wave-function properties serving as triggers for collapse. In particular, Kremnizer and Ranchin (2015) define a scalar wave-function property “quantum integrated information” and use this to determine the rate at which particles in a system collapse onto a position basis. This model departs even further from the standard Copenhagen dynamics, however, by invoking a scalar trigger for the rate of collapse, and by always collapsing onto a position basis. The Kremnizer/Ranchin approach is closer in spirit to spontaneous-collapse approaches of GRW and Pearle, with the difference that the rate of collapse is modulated by the scalar wave-function property in question.

Still, an approach on which measurement is a wave-function property is perhaps the best bet for a measurement-collapse interpretation that roughly fits the mold of the original Copenhagen interpretation. If a wave-function property $m_{S,O}$ serves as a deterministic trigger, the approach is compatible with the letter of the standard measurement-collapse interpretation: wave functions evolve according to the Schrödinger equation except when measurement occurs, when they undergo collapse according to the Born rule. This approach simply supplements the standard interpretation with a specific definition of measurement as a wave-function property. This involves perhaps the smallest change to the standard measurement-collapse dynamics of any proposal we have seen, though the stipulations are still significant and the overall picture is nonstandard.

7 Conclusion

We have seen that the Zeno problem poses a major challenge to Copenhagen-style measurement-collapse interpretations of quantum mechanics. Responding to it requires either adopting a strong form of mind/body dualism where conscious measurement does not precisely correlate with states of the brain, or adopting an unusual view on which measurement is understood as a special wave-function property that triggers collapse. Both views deserve exploration, but they also require going well beyond the simple framework of the measurement-collapse dynamics.

It is a familiar point that interpretations of quantum mechanics such as those put forward by Bohm, Everett, Ghirardi et al, and Pearle are revisionary relative to the textbook account of quantum mechanics. One might have hoped that a precisified version of the measurement-collapse dynamics would be the best hope for a non-revisionary interpretation of quantum mechanics, but the Zeno dilemma suggests that any such interpretation must be somewhat revisionary. This reinforces the view that there is no adequate non-revisionary interpretation of quantum mechanics.

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