Observation and Quantum Objectivity

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The paradox of Wigner's friend challenges the objectivity of quantum theory. A pragmatist interpretation can meet this challenge by judicious appeal to decoherence. Quantum theory provides situated agents with resources for predicting and explaining what happens in the physical world—not conscious observations of it. Even in bizarre Wigner's friend scenarios, differently situated agents agree on the objective content of physical magnitude statements while, normally, quantum Darwinism permits agents equal observational access to their truth. Quantum theory has nothing to say about conscious experiences. But it does prompt us to reexamine the significance of everyday claims about the physical world.

1. Introduction. Wigner (1967) presented his friend paradox to motivate the view that consciousness has a special role to play in quantum theory—by collapsing the quantum state. In a more recent discussion, D'Espagnat (2005) argued that a consistent treatment of the Wigner's friend scenario may be given (without collapse) if the descriptive content underlying quantum theory is restricted to probabilistic predictions flowing from the Born rule, but only if these concern conscious experiences of observers. In contrast, a recent pragmatist proposal (Healey 2012) views quantum theory as a resource for situated *agents* (rather than observers) with no requirement that these be conscious.[1] If quantum theory is interpreted along these pragmatist

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1. As far as we know, conscious humans are the only agents currently able to avail themselves of this resource. But this view admits the possibility that nonhuman, or even nonconscious, situated agents may come to use quantum theory.

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lines, Wigner's friend scenarios may be treated consistently and without ambiguity.

The article proceeds as follows. Section 2 analyzes some distinct notions of objectivity relevant to quantum theory. Section 3 recalls the paradox of Wigner's friend. The pragmatist interpretation of Healey (2012) is sketched in section 4. Section 5 shows how this resolves the paradox while securing the objectivity of description in quantum theory. Section 6 addresses a more general worry about objectivity of description. Section 7 relates the foregoing treatment of objectivity to a recent suggestion (Ollivier et al. 2004) that objective properties emerge from subjective quantum states through quantum Darwinism. While a pragmatist view of quantum theory secures the objectivity of a claim about the values of physical magnitudes, it recognizes that its content depends on the environmental context. The conclusion points out that this involves a subtle change in our understanding of how even the familiar language of everyday affairs, including laboratory procedures, assigns objective properties—beables—to objects (Bell 2004).

2. Objectivity. Objectivity (and its polar opposite, subjectivity) can mean many things. Dreams are a paradigm of subjectivity. The subject matter of a dream is not objective: a dream does not portray what really happens. The mode of presentation is not objective: this subject matter is accessible only to the dreamer. What is presented as well as its mode of presentation strongly depends on the specific as well as the general features of the dreamer—her individual physiology, psychology, and prior experiences as well as her humanity (Dick 1968). By contrast, a description or mathematical representation in physics has an objective subject matter if its content represents physical reality, and an objective mode of presentation to the extent that how this is represented does not depend on the specific and general features of the one whose representation it is.

The prominence of notions of observation or measurement in standard formulations of quantum theory raises concerns about the objectivity of descriptions in that theory. If the Born rule is understood to yield probabilities just for results of observations/measurements, then one can question the objectivity of these results. The orthodox view—that a quantum measurement cannot be understood generally as revealing the value of the measured observable—has now been amply supported by "no-go" theorems (Gleason 1957; Kochen and Specker 1967; Fine 1982; Mermin 1993). This challenges the objectivity of subject matter in a description of the result of an observation. One can respond to this challenge by proposing an analysis of observation/measurement as an objective physical process. But the assumption that quantum theory can itself represent this process leads to the notorious quantum measurement problem (Fine 1970; Brown 1986; Bassi and Ghirardi 2000). The alternative of characterizing observation indepen-

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dently as a physical interaction with a macroscopic apparatus and/or involving irreversible amplification involves the "shifty split" between quantum and classical descriptions justifiably criticized by Bell (2004).

With his keen appreciation of how difficult it is to provide a satisfactory physical characterization of observation/measurement in quantum theory, Wigner came to think that a measurement in quantum theory occurs just when a conscious observer becomes aware of a result. On this view, the Born rule yields probabilities only for alternative conscious experiences. It thereby threatens both the objectivity of the subject matter of description in quantum theory and the objectivity of its mode of presentation. Quantum theory, it seems, is then concerned to predict and (perhaps) explain "communicable human experience. In other words . . . the set of all the impressions human minds may have and communicate to others" (D'Espagnat 2005, 1965).[2]

Suppose one so restricts the scope of quantum theory. Then the descriptive claims to which the Born rule attaches probabilities fail to be objective in several respects:

1. Their subject matter is not a physical reality independent of our experiences.
2. Their mode of presentation depends on the individual consciousness.
3. This consciousness is generically *human*.[3]

One could seek to restore this third aspect of objectivity by generalizing beyond humans to observers capable of any sufficiently sophisticated form of conscious experience. But since consciousness is not well understood (especially in nonhumans), to do so would further obscure the content of these descriptive claims, which would still fail to be objective in either of the first two respects.

While the quantum theory of environmental decoherence does not by itself resolve the quantum measurement problem (D'Espagnat 1990; Bub 1997; Adler 2000), many believe it may contribute to a resolution within some appropriate interpretative framework. Such a framework appears in Healey (2012) and is sketched in section 4 below. From the present perspective, the key interpretative proposal is to remove any talk of observation or measurement from a formulation of the Born rule by taking this to generate a function with the mathematical features of a probability measure over claims that simply describe values of magnitudes rather than results of observing them. The

2. The Wigner's friend scenario casts doubt even on such communicability. D'Espagnat's paper seeks to relieve this doubt.

3. In the course of the article, I will distinguish further aspects of objectivity. The notion is many-faceted, so it is best not to begin by defining objectivity in an attempt to encompass them all.

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no-go theorems block this approach if one further assumes that every claim over which these functions are defined always has a well-defined content, so an agent should believe it to a degree specified by its Born "probability" to avoid refutation by statistics of actual observations.[4] But suppose, however, that how much significance attaches to a claim about a system depends on the extent of environmental decoherence suffered by its quantum state. Then the numbers yielded by the Born rule have the import of genuine probabilities only for significant claims: Born rule probabilities for claims lacking such significance are not reflected in (actual or hypothetical) frequencies and should not guide an agent's degrees of belief in these insignificant claims.

On this view, any reference to observation or measurement has been eliminated from the Born rule as well as other basic principles of quantum theory, and so there is no reason to suppose that descriptive claims that arise in quantum theory are subjective in any of the points 1–3 noted above. But there is a fourth aspect of objectivity to consider, as the following quote makes clear: "A view or form of thought is more objective than another if it relies less on the specifics of the individual's makeup and position in the world, or on the character of the particular type of creature that he is" (Nagel 1986, 5).

If the significance for an agent of a descriptive claim about the value of a magnitude depends on how that agent is situated in the world, then that claim may lack a kind of objectivity. Differently positioned agents could understand the claim differently: they may come to a no-fault disagreement about whether it is true, or even meaningful. The interpretation of Healey (2012) faces such a challenge to its understanding of the objectivity of descriptive claims in quantum theory—a challenge that is highlighted by the Wigner's friend scenario, as we shall see.

3. Wigner's Friend. The "paradox" of Wigner's friend presents a challenge to the objectivity of physical description within quantum theory. To set up the paradox, imagine Schrödinger's cat (and associated 'diabolical device') replaced by a human experimenter (Wigner's friend, John) who records in a device D the result of a quantum measurement of observable Q he performs on a system s inside his isolated laboratory.[5] Eugene and John both agree that

4. "Probability" rather than probability, because here the function has the mathematical character of a probability measure, but the theorems show its values cannot play probability's requisite practical and/or epistemic role.

5. To call the laboratory 'isolated' is to require by fiat the absence of any decohering interactions with its external environment. So we are talking of a ridiculously impractical *Gedankenexperiment*, as Schrödinger explicitly said he was when describing his cat scenario. The point of doing so is to show how this raises a problem for one view of quantum theory and then to explain why this problem does not arise on the pragmatist view of Healey (2012).

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the quantum state of s is initially (at time t_i) a nontrivial superposition of eigenstates of $\hat{Q}$. Let C be the claim that the value of a recording magnitude M on D is m at time t_f after s has interacted with D. John looks at D at t_f and makes claim C. On the basis of this observation, he assigns a collapsed quantum state to $s + D$.[6] Environmental interactions within the laboratory rapidly entangle this collapsed state with the state of everything else in the laboratory. But the total quantum state $|\psi_J\rangle$ of the enormously complex system composed of John, D, and everything else inside the laboratory will continue to reflect the collapse onto an eigenstate of $\hat{M}$ induced by John's measurement.

Meanwhile, Eugene, who has remained outside the laboratory, assigns a state $|\psi_E\rangle$ to the enormously complex system composed of John, D, and everything else inside the laboratory, based on all the information about the properties of systems to which he has access in this situation. For Eugene, John's measurement involves purely unitary interactions—between s and D, between D and John, and between all these systems and the rest of the laboratory. Accordingly, he evolves the state $|\psi_E\rangle$ unitarily, with no collapse from t_i to t_f. Since $|\psi_J(t_f)\rangle \neq |\psi_E(t_f)\rangle$, John's and Eugene's quantum states differ after John's measurement but before Eugene enters the laboratory. As these states are usually understood, $|\psi_J(t_f)\rangle$ represents a definite result of John's measurement (recorded by the state of D, John's memory, etc.) while $|\psi_E(t_f)\rangle$ excludes any such definite result and its traces. To retain its internal consistency, this view of quantum states must deny the objectivity of John's measurement result, since differently situated agents (John and Eugene) disagree about whether C is true at t_f.

On any view of quantum states, since $|\psi_E(t_f)\rangle$ is an eigenstate of some extremely complex observable O on the entire laboratory system, Eugene could in principle (though certainly not in practice) distinguish between $|\psi_J(t_f)\rangle$ and $|\psi_E(t_f)\rangle$ by creating a suitable ensemble of identical laboratory systems and measuring O on each system: $|\psi_E(t_f)\rangle$ would give the same result on each, while $|\psi_J(t_f)\rangle$ would almost certainly yield a statistical spread of different results. This same procedure would also, in principle, enable Eugene to distinguish between $|\psi_E(t_f)\rangle$ and the mixed state $\rho_J(t_f) = \sum_i |c_i|^2 |\psi_J(t_f)\rangle_i \langle\psi_J(t_f)|_i$. Eugene may assign to reflect his ignorance of the result of John's measurement.[7]

6. He does so in accordance with a view of quantum states due to Dirac and von Neumann. While himself subscribing to this orthodoxy, Wigner maintained that it is only John's consciousness that induces the collapse. I use the word 'collapse' to refer to a hypothetical physical change in the properties of a system supposedly represented by a reassignment of its quantum state.

7. To keep things simple, here I assume John made an ideal measurement on the state $\sum_i c_i|\varphi_i\rangle$, thereby collapsing the state of $s + D$ onto some eigenstate $|\varphi_k\rangle|\chi_k\rangle$ with probability $|c_k|^2$.

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Wigner's own way of resolving this paradox was to give consciousness (and only consciousness) the distinctive physical role of inducing collapse of the quantum state onto an eigenstate of the measured observable. For him, it was the interaction with John's consciousness that produced a discontinuous physical change inside the laboratory, resulting in the final state $|\psi_J(t_f)\rangle$ and not $|\psi_E(t_f)\rangle$. Such a change would be detectable in principle in the Wigner's friend scenario, though quite impossible to detect in practice. I will offer a different resolution involving no such collapse. This involves the different understanding of quantum states described in the next section.

4. A Pragmatist Interpretation. In quantum theory as it is usually formulated, theoretical models involve quantum states and operators corresponding to observables (including the Hamiltonian and/or Lagrangian) and (solutions to) the Schrödinger equation and relativistic generalizations. But there is still no agreement as to how, or whether, any of these model elements represent physical magnitudes.

According to Healey (2012), operators, quantum states, and their evolution neither represent nor describe the condition or behavior of a physical system to which they pertain. It follows that these novel elements appearing in quantum models cannot be used to make claims about how the behavior of that system is responsible for any physical phenomenon. But quantum theory nevertheless helps us to predict and explain an extraordinary variety of physical phenomena using representational resources from outside of quantum theory. It can do this because of the way in which theoretical models involving quantum states, operators, and the Schrödinger equation are applied. There are principles for using these models to guide one in making descriptive claims and forming representational beliefs about physical systems to which such models may be applied but which these models do not themselves describe or represent.

The dispute as to whether quantum theory provides a complete description of a physical system presupposes that quantum states at least provide a partial description or representation of the physical properties of systems to which they are assigned. Rejecting this presupposition may seem tantamount to regarding the quantum state as merely a symbolic device for calculating probabilities of possible measurement outcomes on these systems. But this is not so. Assignment of a quantum state may be viewed as merely the first step in a procedure that licenses a user of quantum theory to express claims about physical systems in descriptive language and then warrants that user in adopting appropriate epistemic attitudes toward these claims. The language in which such claims are expressed is not the language of quantum states or operators, and the claims are not about probabilities or measurement results: they are about the values of magnitudes on physical systems. That is

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why Healey (2012) refers to such claims as NQMCs—nonquantum magnitude claims. Here are some typical examples of NQMCs:

> A helium atom with energy −24.6 electron volts has zero angular momentum.
>
> Silver atoms emerging from a Stern-Gerlach device each have an angular-momentum component either $+\hbar/2$ or $-\hbar/2$ in the z-direction.
>
> The fourth photon will strike the left-hand side of the screen.
>
> When a constant voltage V is applied across a Josephson junction, an alternating current I with frequency $2(e/h)V$ flows across the junction.

(Note that two of these nonquantum claims are stated in terms of Planck's constant.) For contrast, here are some quantum claims that do not describe the physical properties of systems to which they pertain:[8]

> The expectation value of angular momentum for atomic helium in the ground state is 0.
>
> Integral-spin systems have symmetric quantum states, while half-integral-spin systems have antisymmetric quantum states.
>
> The probability that a tritium nucleus will decay in 12.3 years is 1/2.
>
> After one photon from the polarization-entangled Bell state $|\Phi+\rangle$ is found to be horizontally polarized, the other photon has polarization state $|H\rangle$.

This is not to say that quantum mechanical claims like these lack truth-values—each is appropriately evaluated as true (though in the case of the last claim, that evaluation is critically dependent on the context relative to which it is made).[9] But the function of such claims is not to describe or represent

8. In the pragmatist interpretation of Healey (2012), a quantum claim is not to be distinguished from an NQMC by the fact that it concerns some wholly new dynamical variable. Spin is still a form of angular momentum, even though quantum theory uses noncommuting spin-component operators in its models and severely restricts entitlement to claims about spin-component values and their relation to NQMCs about position and momentum.

9. To call these claims true is, in part, to say that they command the assent of all rational, well-informed agents. Price (2003) is one pragmatist's attempt to say what more is involved. A distinction between descriptive and nondescriptive claims is not to be drawn solely in terms of the function of a claim and can only be contextual for a pragmatist. A doctor's claim that his patient should quit smoking and exercise more may be considered true while its function is to prescribe a course of action. Interpreting quantum theory sets

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properties of physical systems: it is to offer authoritative advice to a physically situated agent on the content and credibility of NQMCs concerning them. Quantum theory contributes indirectly to our predictive and explanatory projects.

A quantum state and the consequent Born probabilities can be assigned to a system only relative to the physical situation of an (actual or hypothetical) agent for whom these assignments would yield good epistemic advice. What one agent should believe may be quite different from what another agent in a different physical, and therefore epistemic, situation should find credible. This relational character of quantum states and Born probabilities does not make these subjective, and it may be neglected whenever users of quantum theory find themselves in relevantly similar physical situations. NQMCs are not relational in this way: their truth-values do not depend on the physical situation of any actual or hypothetical agent.

On this pragmatist understanding, a quantum state guides an agent in two different ways. The agent requires guidance in assessing the content of NQMCs about systems of interest in a context where such claims may arise. It is often said that assignment of a value to an observable on a system is meaningful only in the presence of some apparatus capable of measuring the value of that observable. But some account of meaning must be offered in support of this assertion, and the extreme operationist account that is most naturally associated with it would be unacceptably vague even if it were otherwise defensible. Exactly what counts as the presence of an apparatus capable of measuring the value of an observable?

Contemporary pragmatist approaches to meaning have the resources to provide a better account of the significance of an NQMC about a system, as entertained by an agent, in a context in which that system features. A pragmatist like Brandom (1994, 2000) takes the content of any claim to be articulated by the material inferences (practical as well as theoretical) in which it may figure as premise or conclusion. These inferences may vary with the context in which a claim arises, so the content of the claim depends on that context. The quantum state modulates the content of NQMCs about a system by specifying the context in which they arise. The context may be specified by the nature and degree of environmental decoherence suffered by this quantum state. An NQMC about a system when the quantum state has exten-

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up a context in which it is appropriate to grant the descriptive function of NQMCs while assessing the function of quantum claims with respect to them. While that function is not to describe or represent quantum systems, the successful performance of its function is what warrants assent to a quantum claim. There is a semantically minimal sense in which a quantum claim true of a system now corresponds to reality. But its truth is grounded, not in some present quantum property of this system, but rather in true NQMCs, many if not all of which say what other systems were or will be like.

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sively decohered in a basis of eigenstates of the operator corresponding to that magnitude on the system has a correspondingly well-defined meaning: a rich content accrues to it via the large variety of material inferences that may legitimately be drawn to and from the NQMC in that context. Call an NQMC canonical if it is of the form $M \in \Delta$:

Magnitude M has value in Borel set Δ of real numbers.

Only when the content of a canonical NQMC is sufficiently well articulated in this way is it appropriate to apply the Born rule to assign a probability to that claim.

For example, a claim that an electron passed unobservably through a particular slit in a diffraction grating figures as premise or conclusion in almost no interesting material inferences and so is very poorly articulated. This is a consequence of the fact that, in the absence of interactions capable of revealing its presence, the quantum state of the electron suffers negligible decoherence through entanglement with the environment in the interferometer. With no significant decoherence between different spatially localized quantum states, an agent has only a very limited license to use claims about the electron's position. In particular, the license is so limited that little may legitimately be inferred from such claims. But the subsequent interaction with detectors at the screen involves massive environmentally induced decoherence of the initial quantum state of electron plus detector, permitting a high degree of articulation of the content of claims about the value of a magnitude on the detector taken to record the position of the electron at the screen. The decohered quantum state then grants an agent a wide license to formulate and use NQMCs about records of the electron's position at the screen. This illustrates the first way in which a quantum state guides an agent—by advising her on the extent of her license to use particular NQMCs by informing her of the nature and degree of that state's environmental decoherence.

With a sufficiently extended license, an agent may now apply the Born rule to evaluate the probability of each licensed canonical NQMC using the appropriate quantum state. In the example, this will be the initial superposed state of the electron. Lacking more direct observational information, after assigning the quantum state of a system appropriate to her physical situation, an agent should adjust her degrees of belief in licensed NQMCs pertaining to that system so they match the probabilities of NQMCs specified by the Born rule. This is the second way in which a quantum state guides an agent.

An agent should accept this twofold guidance by the quantum state appropriate for one in her physical situation, since by doing so she is able successfully to predict and explain phenomena in a wide variety of circumstances. But according to Healey (2012) she need not, and should not, assume

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that this quantum state describes or represents the condition or behavior of a system to which she ascribes it. The interpretation does not deny that a particular process occurs when a physical system interacts with its physical environment. But it does deny that the function of a model of decoherence of a system's quantum state is to represent what happens to that system in this process: that is the sense in which decoherence is not itself a physical process. An agent appeals to the quantum theory of decoherence to decide what to think about the content and credibility of NQMCs about a physical system, not to describe the evolving properties of a system whose quantum state decoheres.

5. Paradox Resolved. Consider the situation of Wigner's friend John inside his isolated laboratory. According to the pragmatist interpretation sketched in the previous section, John is licensed by decoherence to apply the Born rule to the superposed state of s and advised by quantum theory to adjust his credences in claims about the value of recording magnitude M on D at time t_f so they match the corresponding Born probabilities. This is because the phase of the quantum state he consequently assigned to $s + D$ immediately before has, by t_f, been robustly delocalized into the environment inside his laboratory. He is then warranted by his own direct observation of D in making the significant claim C that the value of M on D is m.

Meanwhile, Eugene, who has remained outside the laboratory, assigns state $|\psi_E\rangle$ to the enormously complex system composed of John, D, and everything else in the laboratory. By assumption, the phase of state $|\psi_E\rangle$ has not been delocalized into its environment by t_f, so this state does not license Eugene to entertain any significant claim about the value of a magnitude on the laboratory or anything in it. In this situation, Eugene should not apply the Born rule to $|\psi_E\rangle$ and adjust any of his credences accordingly. If and only if the laboratory ceases to be isolated so as to delocalize the phase of $|\psi_E\rangle$ (as Eugene subsequently enters it, for example) would Eugene be in a position to apply the Born rule to significant claims about the laboratory or traces it leaves in an external recording device (such as his own brain).

Recall the difficulties presented by the Wigner's friend scenario noted in section 3:

1. As these states are usually understood, $|\psi_J(t_f)\rangle$ represents a definite result of John's measurement (recorded by the state of D, John's memory, etc.) while $|\psi_E(t_f)\rangle$ excludes any such definite result and traces of it in John's laboratory.
2. On any view of quantum states, since $|\psi_E(t_f)\rangle$ is an eigenstate of some extremely complex observable O on the entire laboratory system, Eugene could in principle (though certainly not in practice) distinguish between $|\psi_E(t_f)\rangle$ and $|\psi_J(t_f)\rangle$ (or $\rho_J(t_f)$) by creating a suitable en-

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semble of identical laboratory systems and measuring O on each system.

These difficulties present a challenge to the objectivity of physical description here. Point 1 apparently implies that, by assigning different quantum states to the contents of John's laboratory at t_f, John and Eugene come to disagree about the truth-value of the descriptive claim C. If so, they can both be right only if that truth-value is relative to the physical situation of the agent making it—in conflict with the fourth aspect of objectivity noted in section 2. But point 2 shows that such relativization of truth-value to agent-situation still leaves it unclear how John and Eugene can consistently apply quantum theory here. Independent of the practicality of Eugene's discriminatory measurements, $|\psi_E(t_f)\rangle$ and $|\psi_J(t_f)\rangle$ (or $\rho_J(t_f)$) are distinct states, yielding incompatible Born probabilities concerning the possible values of certain magnitudes on the entire laboratory. Relativization of the laboratory's quantum state to the situations of Eugene and John, respectively, leaves it ambiguous on which of these states quantum theory advises them to base their expectations about these possible values.

The pragmatist of the previous section responds to this challenge, first by rejecting the usual understanding of the states $|\psi_J(t_f)\rangle$, $|\psi_E(t_f)\rangle$. For her, neither state has the function of representing the physical properties of John's laboratory or anything in it. Since neither state represents anything bearing on the result of John's measurement (e.g., whether or not C is true at t_f), assignment of both states to John's laboratory at the same time could not lead John and Eugene to assign (apparently) conflicting truth-values to C.

But John and Eugene each assume that John will perform a measurement on s by interacting s appropriately with D and that the environment inside the laboratory will decohere the state of $s + D$ in D's "pointer basis" (without inducing any physical collapse in that state). So both John and Eugene are licensed to entertain claim C and (beforehand) to set their credences for C at t_f equal to the corresponding Born rule probability. This implies they agree that C has a truth-value at t_f. But while Eugene remains outside the laboratory, only John is in a position to look at D at and after t_f and so determine what that truth-value is. This secures the objectivity of the description C, in the sense that differently positioned agents (John and Eugene, in this case) agree that C has a truth-value after t_f and do not disagree about what that truth-value is. At this stage, John, but not Eugene, is in a position to *know* that C is true rather than false. Eugene can choose whether or not to enter the laboratory to try to find out whether C is true.

Suppose Eugene decides to see for himself the outcome of John's observation by entering the laboratory just after t_f. This will decohere the phase of $|\psi_E(t_f)\rangle$, permitting Eugene to apply the Born rule to this state to adjust his degrees of belief in various significant claims about the contents of the lab-

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oratory, including C, John's record of the outcome in his notebook, John's verbal report, and so on, as well as correlations between such claims. The Born probabilities of these claims (joint as well as single) based on the state $|\psi_E(t_f)\rangle$ will lead him to the following confident expectation: whatever may be the outcome of John's observation, the laboratory will contain multiple mutually supporting records of it. Nothing about $|\psi_E(t_f)\rangle$ will tell him what John's outcome actually was. But he can easily find that out by asking John and observing any of the other multiple, correlated records inside the laboratory. The important point is that $|\psi_E(t_f)\rangle$ does not exclude an outcome at t_f, so by entering the laboratory Eugene simply finds out what happened—he does not *make* it happen.

If Eugene were instead (able) to remain outside the laboratory but interact with it so as to measure the value of O, he should use $|\psi_E(t_f)\rangle$ to calculate a Born probability of 1 that a suitable recording device, applied to the laboratory and decohered in its pointer basis by external environmental interactions, will record a value of O equal to the eigenvalue of its corresponding operator in state $|\psi_E(t_f)\rangle$. Even though Eugene assumes that John records the outcome of his measurement at t_f, by t_f there has been no physical interaction between Eugene and anything inside the laboratory that could serve to inform Eugene of that outcome. So Eugene cannot base his expectation of the outcome of a measurement of O on $|\psi_J(t_f)\rangle$ and would be mistaken if he were to base that expectation on $\rho_J(t_f)$. There is no ambiguity about to what state Eugene should apply the Born rule when setting his credences concerning the outcome of his O-measurement.

On what quantum state should John base his credence as to the outcome of an external O-measurement? The outcome of John's measurement should prompt him to update the quantum state he assigns to certain subsystems of his laboratory so as to take account of the new information he has acquired. For example, since he takes C not only to have a high content at and for some time after t_f but also to be true then (based on his own observation of D), his state assignment to D should reflect this. So he should not only believe C but also assign D a quantum state that assigns Born probability 1 to C—the state $|\chi_m\rangle$, an eigenstate of $\hat{M}$ with eigenvalue m (or, more realistically, a mixture of degenerate eigenstates with this eigenvalue). This is how he squares the inferences to which C entitles him—that repeated observations of D will confirm the continued truth of C—with credences based on application of the Born rule to the quantum state he assigns to D.

He may go on to assign quantum state $|\varphi_m\rangle|\chi_m\rangle$ to $s + D$ if he has justified confidence that the interaction has not disturbed s, since his expectations based on that state would then be borne out, even concerning measurements in his laboratory of correlations between dynamical variables on s and D. That will be so only because phase relations between the states of s and of D have been delocalized by their environment within the labo-

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ratory. But if he were to consider the entire contents of his laboratory, he would have to acknowledge that the outcome of an external O-measurement by Eugene on this vast composite system would be sensitive to phase relations between its subsystems that have *not* been decohered by any environmental interactions, since (by hypothesis) there has been no interaction between the laboratory and its external environment. So he would be mistaken to base his credence as to the outcome of an external O-measurement on assignment of state $|\psi_J(t_f)\rangle$ to the entire system these compose. He can hypothetically take the perspective of Eugene, but if he does so he must then assign the same state $|\psi_E(t_f)\rangle$ that he agrees is the correct state for someone in Eugene's situation. There is no ambiguity as to which quantum state should be used to calculate Born probabilities for the results of an external O-measurement performed on the entire laboratory, in the sense that differently positioned agents (John and Eugene, in this case) agree on this state. Of course, only Eugene is then in a position to make such a measurement.

What will Eugene find if he enters the laboratory after measuring the value of O in this way? D will no longer have a record of the truth of C. Even if John still exists, he will not remember that C was verified as true at t_f. Because $\hat{O}$ fails to commute with $\hat{M}$, as well as each operator corresponding to an effective "pointer observable" on every other system correlated with this through interactions within the laboratory, the external interaction required to record the value of O will have so disturbed the laboratory and its contents as to remove all traces that C was true at t_f. But one cannot change the past: C was indeed true at t_f, as John then verified with his own eyes.

There is, in principle, an even more dramatic way to erase all traces of C. Since the entire laboratory and its contents constitute an isolated system, Eugene will take $|\psi_E\rangle$ to have evolved unitarily from its state $|\psi_E(t_i)\rangle$ prior to John's measurement on s to its state $|\psi_E(t_f)\rangle = U_{if}|\psi_E(t_i)\rangle$. The state Eugene should ascribe to the contents of the laboratory at t_i should reflect his belief that his friend has not yet performed the planned measurement: this will assign Born probability 1 to claims about D, John, and other items in the laboratory that suffices to substantiate this full belief. Mathematically, there will exist a Hamiltonian that would induce the time-reversed evolution of $|\psi_E\rangle$ so that at a later time t_g (where $t_g - t_f = t_f - t_i$) it is restored to its value before John's measurement: $|\psi_E(t_g)\rangle = U_{fg}^{\dagger}|\psi_E(t_f)\rangle = |\psi_E(t_i)\rangle$.

If Eugene had the powers of a quantum demon, he could instantaneously replace the original Hamiltonian by this time-reversing Hamiltonian at t_f, thereby restoring $|\psi_E\rangle$ at t_g to its original value at t_i. Suppose that he does so and postpones his entry into the laboratory until t_g. Since the quantum state of the entire laboratory is identical to what it was before John had made any measurement, Eugene must fully expect that if he then asks John about the result of his measurement, John will say he has not yet performed any measurement. He must further fully expect that his own examination at, and

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at any time after, t_g of D, John's notebook and anything else inside the laboratory will reveal no record of any such measurement ever having been made. Eugene's action at t_f has, by t_g, erased all traces of John's measurement and its result: indeed, Eugene has succeeded in erasing all traces of everything that happened inside the laboratory between t_i and t_f. Once again, he has not changed the past. But there has been a wholesale loss of history, understood as reliable information about the past. This point will be pursued in the concluding discussion. The present section has shown how the pragmatist view of Healey (2012) maintains the objectivity of physical description in the Wigner's friend scenario.

6. Objectivity Secured. According to Healey (2012), John inside the laboratory and Eugene outside do not assign inconsistent truth-values to claim C. Moreover, each assigns the same rich content to C based on the decoherence of the state of $s + D$ induced by environmental interactions inside the laboratory. This certifies the (fourth aspect of the) objectivity of C in the Wigner's friend scenario: John and Eugene agree not only on the truth-value but also on the content of claim C, despite their different physical situations. The certification depends on the fact that both John and Eugene apply essentially the same model of decoherence to the same initial quantum state of $s + D$.

But there is an objection to be faced. According to Healey (2012), while quantum states are objective, they are also relational: the quantum state an agent should assign to a system generally depends on the (actual or hypothetical) physical situation of that agent. If differently situated agents assign different quantum states to a system, this raises the possibility that their models of its decoherence will so differ as to lead each to assign a different content to certain claims concerning it. Relativization of quantum state ascriptions threatens relativization of the content of NQMCs like C. This would undermine their objectivity in the fourth respect pointed out in section 2.

Now even though John and Eugene are differently situated in the Wigner's friend scenario, each can choose to adopt the perspective of the other's situation for the purpose of applying quantum theory. Eugene should assign the same initial state as John to s because each knows that this is the state on which John will perform his measurement. Eugene and John are each in the same state of ignorance as to the initial state of D and its (lack of) correlations with that of s, so there is no reason for them to assign different states either to D alone or to $s + D$. (Their conclusion—that interactions within the laboratory robustly decohere the state of $s + D$ and so endow C with rich content—is not sensitive to fine details of the initial state of $s + D$.)

One might object that Eugene's physical situation requires him to assign the state $|\psi_E\rangle$ to the contents of the laboratory and that, since the phase of $|\psi_E\rangle$ is not delocalized into its environment, Eugene should not assign a

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rich content to C. An alternative objection would be that C has no unambiguous content for Eugene, since he has no principled reason to base his assessment of that content on the degree of decoherence of the "internal" state of $s + D$ rather than that of $|\psi_E\rangle$.

But in assessing the content of an NQMC such as C about a system (D in this case), an agent like Eugene should base his model of decoherence on quantum state assignments incorporating everything he is in a position to know about the physical situation of D, as represented in nonquantum claims. We have assumed that Eugene is in a position to know that John will initiate a certain interaction between s and D inside the laboratory. Eugene's physical situation does not require him to assign the state $|\psi_E\rangle$ to the contents of the laboratory when assessing the content of C: to do so would be to neglect information to which he has access in this situation that is relevant to assignment of quantum states to s and D.

There are circumstances in which agents are so differently situated that they correctly assign different quantum states to the same system, where each agent's assignment is based on all information to which the agent has access, given her physical situation.[10] If models of decoherence based on such different assignments were to result in these agents assigning different contents to the same NQMC, that could threaten the objectivity of description in quantum theory. To assess the threat, we need to specify how far different agents' state assignments may differ, and how this affects the models of decoherence they should employ in assessing the content of relevant NQMCs.

The example in footnote 10 prompts the following restriction on different agents' state assignments: if Alice assigns a mixed state to a system while Bob assigns a pure state, then Bob's state vector lies in the support of Alice's density matrix. An argument for a generalization of this restriction has been offered (Brun et al. 2002): different agents' state assignments by several density matrices are mutually compatible if and only if the supports of all of them have at least one vector in common.

Suppose differently situated agents (such as Alice and Bob in the example) assign quantum states to a system S that differ in some way consistent with this generalized restriction. Assuming this is the only difference between the models of decoherence they use in assessing the content of NQMCs about S, there are no grounds for thinking they will arrive at different assessments. By assumption, all their models share the generic features of applying the same Hamiltonians to the same initial state of S's environ-

10. This happens, for example, when Alice and Bob perform spacelike separated polarization measurements on an entangled photon pair. Knowing his outcome, Bob can assign a polarization eigenstate to the photon entering Alice's detector. Since this information is not accessible to Alice, she correctly assigns that photon a mixed polarization state.

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ment with the same limitations on prior system/environment entanglement. Since a model with these generic features will decohere the phase of a generic pure state of S to the same extent in the same "basis,"[11] that is how it will model the decoherence of every vector in the Hilbert space in which lies the vector common to the supports of all the states assigned by differently situated agents subject to the generalized restriction. It follows that the model of decoherence each of these agents uses to assess the content of NQMCs about S will lead each agent to the same assessment of the contents of NQMCs about S. This means they will all agree on the content of these NQMCs, thereby securing their objectivity in the fourth respect noted in section 4.

7. Independent Verifiability. It is ironic that observation poses a threat to the objectivity of physical description in quantum theory, since observation is generally used to settle questions about objectivity in science and daily life. Doubting the objective presence of the dagger he saw, Macbeth tried to grasp it: to prove that Banquo's ghost occupied his own place at the table, he pleaded his guests to see for themselves. Classical physics permits multiple, independent observations on a system to verify a claim about its state, since none of these need irremediably disturb that state.

But suppose an individual system is in a wholly unknown quantum state. No single observation on it can reliably disclose its state. Repeated observations are no better, since observing a system typically irreparably disturbs its quantum state. So even if a system's wholly unknown quantum state could be ascertained by a single observation, this finding could not be checked in further observations, either by the original agent or by others. A wholly unknown quantum state of an individual system is not as objective as a corresponding classical state in yet another, epistemic sense: it is not independently verifiable. Ollivier et al. (2004, 1) put the point like this: "The key feature distinguishing the classical realm from the quantum substrate is its objective existence."

They propose what they call an operational definition of objectivity for a property of a quantum system, according to which such a property is simultaneously accessible to many observers who are able to find out what it is without prior knowledge and who can arrive at a consensus about it without prior agreement. Their idea is that such a property is objective to the extent that multiple records of it exist in separate portions of the environment, so that "observers probing fractions of the environment can act as if the system had a state of its own—an objective state" (Ollivier et al. 2004, 3). They say that "The existence of an objective property requires the presence of its

11. The scare quotes mark the need to allow for models in which decoherence effectively "diagonalizes" s's density operator in an overcomplete basis of narrow Gaussian states.

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complete and redundant imprint in the environment as necessary and sufficient conditions" (2).

While Ollivier et al. (2004) never say exactly what they mean by a property, it seems clear they would count an NQMC locating a value in Δ of a magnitude M on system S as a property assignment to S.

The state of a system in classical physics is specified by a point in phase space: this is equivalent to an assignment of a value to each magnitude on that system, that is, an assignment of a property locating that value in a unit set. The authors' stand-in for the objective state of an open quantum system is one of the eigenvectors of the system observable corresponding to the pointer magnitude that is selected by environmental decoherence. An NQMC locating a value in Δ to the pointer magnitude on system S is taken to assign S an objective property solely on the grounds that a complete and redundant imprint is present in the environment. There are other magnitudes on S represented by operators each of whose eigenvectors is close to an eigenvector of the pointer observable. An NQMC locating a value in Δ to such a magnitude on system S also counts as assigning S a reasonably objective property because of a complete and (slightly less) redundant imprint in the environment. Their idea seems to be that the proliferation of imprints of properties of a quantum system in its environment progressively objectifies its properties until these come to mimic properties that characterize a classical state. An eigenvector of the pointer observable stands in for an objective state by specifying what properties of the system are objectified by the environmental interactions to which it is subjected: "Amplification of a preferred observable happens almost as inevitably as decoherence, and leads to objective classical reality" (Ollivier et al. 2004, 3).

This is quantum Darwinism: "the idea that the perceived *classical reality* is a consequence of the selective proliferation of information about the system" (Ollivier et al. 2004, 3). It is not an account of classical reality or of the actual objective state of a quantum system. If I have understood it correctly, it is an account of how independent acts of observation on a system's environment can produce consensus on properties of a quantum system irrespective of whether or not that system has such properties. One is reminded of Wittgenstein's remark in his *Philosophical Investigations*: "As if someone were to buy several copies of the morning paper to assure himself that what it said was true" (1953, 94e).

Wittgenstein's avid reader is actually in better shape than multiple quantum observers. The morning paper may have correctly reported what happened. But if no NQMCs about a quantum system are true, then it lacks the properties observers attribute to it, so whatever proliferates is in fact *misinformation*. It is important not to be misled by the causal language of imprints into thinking that objective properties of the environment are caused by objective properties of a decohered quantum system. As it stands, quantum

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Darwinism (Ollivier et al. 2004) fails to provide an adequate account of objectivity in the sense of the independent verifiability of NQMCs because it does nothing to show how either those NQMCs or claims about their environmental imprints can be objectively true, given the quantum states of system and environment. Groupthink does not amount to intersubjective verification. But the pragmatist view of Healey (2012) can help the quantum Darwinist take this crucial last step: and after he has taken it, he can be recruited as an ally in the common cause of securing the objectivity of quantum description. The contribution of quantum Darwinism is then its account of how NQMCs that are already objectively true can come to be widely known, even when they concern extraordinarily sensitive physical systems.

Decoherence endows certain NQMCs with a significant content that requires even differently situated agents to seek agreement on their truth-values. When a system is decohered by its environment, these will include claims about the value of its pointer magnitude. They will also include claims about magnitudes on subsystems of the environment that are correlated with the system's pointer magnitude. Since properties not only of the system but also of subsystems of its environment are in this sense objective, it makes sense to ask whether objective claims about a system can be independently verified by observing various portions of its environment. Quantum Darwinism may now offer illuminating answers to this question by providing quantum models of interactions between a quantum system and its multipartite environment. This is a way to show how differently situated agents can come to agree on the truth-values of significant NQMCs about a system without disturbing its state.

8. Conclusion. Reflection on the paradox of Wigner's friend has persuaded some people that quantum theory cannot be understood without careful attention to the role of conscious human experience (Wigner 1967; D'Espagnat 2005). But a pragmatist interpretation (Healey 2012) permits a consistent and unambiguous treatment of the paradox without reference to consciousness. Situated agents can use quantum theory to make objective claims about the values of magnitudes in the physical world, not just about observations of them. This has helped us to predict and explain an enormous variety of otherwise puzzling physical phenomena. A true claim about the value of a physical magnitude states an objective physical fact. Ordinarily, such facts are readily independently verifiable. But acceptance of quantum theory requires one to countenance the possibility that in extraordinary circumstances, information about the value of a magnitude could be irretrievably erased, making this fact no longer verifiable.[12]

12. I thank a referee for correctly pointing out that this consequence is not peculiar to quantum theory. Classical physics also allows for the (in principle) possibility of rewriting

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A canonical magnitude claim ascribes an objective property to a physical system. But the content of this claim is a function of the environmental context. One is tempted to say that this makes the property ascribed not intrinsic but relational, though an inferentialist view of content should make one suspicious of this distinction. In the case of quantum field theory, it implies that any claim about particles has a well-defined content only in some contexts, while other contexts give significance to a claim about (classical) fields. In assessing the content of a claim, an agent should consider the nature and extent of environmental delocalization of coherence. This content does not depend on the (actual or hypothetical) physical situation of the agent, even when agents base their assessments on the different quantum states appropriate to their different physical (and therefore epistemic) situations.

Science is based on observed facts, and quantum theory is no exception. According to Healey (2012), what makes quantum theory exceptional is what it teaches us about the nature of these facts. Bell (2004, 41) introduced the term 'beable' because he thought "it should be possible to say of a system not that such and such may be *observed* to be so but that such and such *be* so."

When making a significant claim about the value of a magnitude on a quantum system, one is saying that it be so, according to Healey (2012). Perhaps this makes this magnitude a beable in Bell's sense. But Bell (2004) goes on to say: "The beables . . . can be described 'in classical terms', because they are there. The beables must include the settings of switches and knobs on experimental equipment, the currents in coils, and the readings of instruments" (52); and "The beables of the theory are those elements which might correspond to elements of reality, to things which exist" (174).

These passages at least suggest that acceptance of quantum theory in no way modifies the content of claims about values of magnitudes—a content that is somehow established by a fixed representation relation that obtains between language and the world (actual, or merely possible if a beable be not)! A pragmatist cannot accept such a representational account of how content accrues to a claim (Brandom 1994, 2000). According to the pragmatist interpretation of Healey (2012), to understand quantum theory, one needs instead to adopt an alternative inferentialist account of what gives a claim content. By modifying the inferential relations between magnitude claims, quantum theory affects their content, rendering this contextual. By making the content of a magnitude claim about a system a function of the environment, acceptance of quantum theory cautions one against taking that claim to attribute an intrinsic property to a noncontextually existing object, even while insisting on the objectivity of the claim. This should make one think differ-

history (e.g., by restoring the exact local situation prior to the melting of an ice cube in a glass of water).

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ently even about the content of everyday claims about ordinary things like the settings of switches and knobs on experimental equipment, the currents in coils, and the readings of instruments.

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