Quantum Theory: Realism or Pragmatism?[1]

La teoría cuántica: ¿realismo o pragmatismo?

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Abstract

During his long and extraordinarily productive career Hilary Putnam occasionally flirted with pragmatism. But his scientific realism provided a fixed point of his attempts to interpret quantum theory. I have argued recently that pragmatist treatments of representation, explanation and probability are keys to understanding how we use quantum theory so successfully, and so how it should be interpreted. For Putnam, scientific realism is itself a scientific hypothesis that explains the success of science. If I am right, the success of quantum theory undermines this kind of scientific realism while supporting a rival pragmatism. Scientific realism remains immune to empirical refutation if it is viewed not as a scientific hypothesis but as a regulative ideal. But a pragmatist view of quantum theory poses a challenge to a certain kind of metaphysical realism.

Keywords: Hilary Putnam, scientific realism, metaphysical realism, pragmatism, quantum theory, measurement problem, non-locality, quantum ontology

Resumen

Durante su larga y extraordinariamente productiva carrera, Hilary Putnam flirteó de vez en cuando con el pragmatism. Pero su realismo científico aportó un punto fijo para sus intentos de interpretar la teoría cuántica. Recientemente he defendido que los tratamientos pragmatistas de la representación, la explicación y la probabilidad son claves para comprender cómo usamos la teoría cuántica con tanto éxito y, así, como debería ser interpretada. Para Putnam, el realismo científico es en sí mismo una hipótesis científica que explica el éxito de la ciencia. Si estoy en lo correcto, el éxito de la teoría cuántica debilita esta clase de realismo científico mientras que apoya un pragmatismo rival. El realismo científico permanece inmune a la refutación empírica

[1] Since writing this paper I have argued that its pragmatist view of quantum theory dovetails with an attractive form of quantum realism: see my "Pragmatist quantum realism", in Steven French and Juha Saatsi, eds. *Realism and the Quantum*, forthcoming from Oxford University Press.

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si se ve no como una hipótesis científica sino como un ideal regulativo. Pero una perspectiva pragmatista de la teoría cuántica plantea un desafío a una cierta clase de realismo metafísico.

PALABRAS CLAVE: Hilary Putnam, realismo científico, realismo metafísico, pragmatismo, teoría cuántica, problema de la medición, no localidad, ontología cuántica.

1. INTRODUCTION

Hilary Putnam profoundly influenced not just my philosophical views but the course of my life. Stimulated by the clarity and urgency of his early writings on quantum theory and impressed by the easy familiarity with physics from which he drew deep philosophical insights, I came to the United States to study with their author. Quantum logic never struck me as a promising way to try to make sense of quantum theory and I was glad when Hilary came to agree. But in his more recent attempts to square quantum theory with scientific realism I see him as putting the philosophical cart before the scientific horse.

During his long and extraordinarily productive career Hilary occasionally flirted with pragmatism. As I have argued in several recent papers, pragmatist treatments of representation, explanation and probability are keys to understanding how we use quantum theory so successfully, and so how it should be interpreted. Scientific realism has provided a fixed point in Hilary's attempts to interpret quantum theory. As he has characterized it, scientific realism is itself a scientific hypothesis that explains the success of science. If I am right, the success of quantum theory undermines this kind of scientific realism while supporting a rival pragmatism.

Scientific realism remains immune to empirical refutation if it is viewed not as a scientific hypothesis but as a regulative ideal. The clarity achieved through pursuit of that ideal by Einstein, Schrödinger and Bell revealed the physical resources of quantum entanglement without yielding a realistic interpretation of quantum theory. A pragmatist may join forces with metaphysically-inclined philosophers, mathematicians and scientists in endorsing the practical value of scientific realism as a regulative ideal for the long-term future of physics while cautioning against its procrustean application to the interpretation of the successful quantum theory we already have. That way is too cheap, as Einstein said of Bohm's 1952 theory[2].

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[2] Letter to Max Born dated 12 May 1952: in Born (1971, p.192).

2. The function of a quantum state

A wave function is a mathematical object often used as representative of the quantum state of a system. In his paper "Quantum mechanics and ontology" Putnam gives his view of the wave function as

> a mathematical object that we use to represent a property of *U* [the physical universe as a whole], much as we use a real number to represent a property when we say that an object has a mass of *x* grams. (2012, p. 152)

In this view, quantum theory is about at least one physical system—the universe—and the role of the wave function is to represent its physical properties. The title of one famous paper[3] notwithstanding, physicists rarely ascribe wave functions to the universe: they assign a wave function (density operator, or other mathematical object) as quantum state to (type or token) systems like electrons, atoms, molecules, spin qubits, superconducting currents, Bose-Einstein condensates, radiation fields in cavities and the interacting quantum fields of the Standard Model. To the extent that he acknowledges such applications of quantum theory, Putnam apparently regards these systems as physical entities, and assumes that the point of ascribing each a wave function as quantum state is to represent its physical properties. Yet he concludes this section by saying that quantum mechanics in its mathematical form doesn't divide up the world into "entities" and "properties" before going on in the next section to stress the need to think seriously about the content of the theory by asking what quantum mechanics is *about*, what it takes to be physically real. I'll return to this question after presenting a very different view of the wave function.

The main reason a physicist ascribes a wave function to a system is not to represent its properties but to be able to say what is likely to happen when it finds itself in various situations. Somewhat more precisely, it is to be able to apply a mathematical algorithm (the Born rule) to that wave function to assign a probability to each of a set of mutually incompatible and jointly exhaustive eventualities that may arise when a system is in a specified situation. The traditional way to characterize an eventuality is as a potential outcome when a magnitude (such as energy or component of position, momentum or spin) is measured: application of the Born rule to the system's quantum state then gives the probability of each possible outcome of any measurement to which that system may be subjected.

[3] Hartle and Hawking (1983).

But the vague, anthropocentric term 'measurement' has no place in a precise formulation of a physical theory, as Putnam recognized long before Bell presented his own forceful objections.[4] So we need a better way of saying what an eventuality is and when it may be realized.

When provided with the relevant wave function, the Born rule assigns probabilities to magnitude claims of the form *M*: **s has (Q$\varepsilon\Delta$)**, locating the value of magnitude *Q* on physical system *s* in set Δ of real numbers (for example, the claim that the energy of a hydrogen atom is less than its 13.6 electron volt ionization energy). In this form, neither a magnitude claim nor the Born rule itself contains any reference to measurement. But a variety of "no-go" theorems shows that, for most quantum systems, not all Born probabilities can be retrieved as marginals of any joint probability distribution for the simultaneous real values of all their magnitudes.[5] These results support the orthodox view that at no time does every magnitude on a quantum system have a precise value—and in particular, that no system ever has a precise position and a precise momentum. For most systems *s*, not all eventualities of the form *M* can consistently be simultaneously realized, in the sense of receiving a well-defined Born probability. We need a "measurement-free" way to restrict the application of the Born rule to a class of significant magnitude claims about a system in a specified situation.

Quantum theory itself can be used as a guide here by application of the theory of decoherence. Application of (unitary) quantum theory to the interaction between a system and (a more or less realistic model of) its environment typically, and extraordinarily rapidly, evolves a (pure) quantum state ascribed to the system robustly into a state represented not by a wave function but by a mixed density operator which is extremely close to diagonal in some "pointer basis" determined by the nature of the interaction with its environment.[6] Claims concerning magnitudes represented by operators near-diagonal in the pointer basis are thereby selected as significant enough to be assigned a probability by the Born rule: the

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[4] Putnam, "A philosopher looks at quantum mechanics" (1965) (reprinted in Putnam (1975)): Bell, "Against 'measurement'" (1989) (reprinted in Bell (2004)).

[5] See especially Kochen and Specker (1967), Fine (1982). Bohmians, of course, appeal to an unorthodox account of magnitudes and their measurement to defend their view that a particle always has a precise position and momentum.

[6] This terminology is unfortunate since the theory of decoherence is by no means restricted to some ill-defined class of "apparatus systems". But it is appropriate at least in so far as many common environmental interactions leave the system density operator approximately diagonal in an (overcomplete) basis of approximate position eigenstates.

Born rule should not be applied to claims concerning magnitudes represented by operators with eigenvectors nowhere near elements of the pointer basis.

Applying quantum theory in this way does not restrict the Born rule to an ill-defined class of measurements. But I suspect that Hilary would raise other objections to this application. Consider the following passage:

> One possible reply is that the time-evolution of the wave function described by the theory can be connected by well-known rules to observable phenomena. But this is just the answer of logical positivism! In effect, the wave function is given an "empirical interpretation" by "coordinating definitions", just as Carnap would have said. But this is not the sort of account that a scientific realist—someone who wants to understand quantum mechanics as describing reality, and not just as a device for making predictions—is seeking. And I am a scientific realist.[7]

In the last two sentences of the passage Putnam simply reiterates his own view of the wave function without argument and notes that it squares with his scientific realist predilections. But in the initial part of the passage he suggests that any alternative view of the wave function according to which it functions as a rule rather than as a representation of physical reality commits some logical positivist error. Here I think he overlooks the possibility of a pragmatist rather than a positivist view of the wave function.

As I see it, the role of the wave function is not to describe or represent some novel physical property, entity or law but to provide good advice to any user of quantum theory about the significance and credibility of magnitude claims about physical systems. It executes its primary function as input to the Born rule. By wholly accepting quantum theory any user commits to adjusting credences in significant magnitude claims to match their Born probabilities. The wave function plays an important preliminary role by advising a user on how significant is each magnitude claim about a physical system in a particular situation. To assess its significance, the user may apply (unitary) quantum theory to that system in interaction with its environment. Given sufficient decoherence, the claim has the significance required to license application of the Born rule to determine its credence. This imposes a contextual selection of which magnitude claims are significant enough to be believed to some degree, and which are not.

7 "Quantum Mechanics and Ontology", in Putnam (2012, p.151): from now on, all references to Putnam's papers specify page numbers in Putnam (2012).

In both roles, the wave function is connected to magnitude claims by a rule. But this is not a semantic rule (an "empirical interpretation" or a "coordinating definition") but a pragmatic rule that prescribes to an agent the appropriate cognitive attitude to adopt toward each relevant magnitude claim. Many of these claims concern physical entities that are in no way observable by unaided human sense organs.

The reader will have noticed a certain "fuzziness" in my statement of the pragmatic rules governing the use of the wave function. This is as unproblematic as it is inevitable. Bell began his "Against 'measurement'" with the complaint that surely by now we should have an exact formulation of some serious part of quantum mechanics. This may be achieved simply by dropping von Neumann's notorious "projection postulate" (collapse of the wave function on measurement) and removing any reference to measurement, observation, apparatus, classical system, etc. from a statement of the Born rule in the way I have indicated. Pragmatic rules governing the use of the wave function should not appear in the resulting exact formulation: They concern the *application* of the theory so formulated. No matter how exactly or precisely a scientific theory is formulated, its application always requires skill and judgment that cannot be made fully explicit. Any pragmatic rule guiding that application remains subject to interpretation by the skilled practitioner.[8]

A good physicist is able to judge when it is permissible to apply the Born rule even without deploying a model of environmental decoherence—fortunately, because environments are typically complex open systems for which there are few tractable quantum models of decoherence and even in these few, completely robust and irreversible diagonalization of system density operator is never more than a *very* good approximation.

I have begun to contrast this pragmatist view of the wave function with Hilary's realist view. It is now time to say why the pragmatist view is better. In each of the next three sections I briefly describe what many have taken to be a deep conceptual problem faced by quantum theory and then indicate why there is no problem if one adopts a pragmatist view.

[8] While stressing that rules governing the use of the wave function are pragmatic rather than semantic, I am sympathetic to the suggestion that Wittgensteinian considerations about rule following may similarly render semantic rules ineliminably "fuzzy".

3. Why there is no measurement problem

The notorious measurement problem has plagued the foundations of quantum theory for well over 50 years. From many formulations of the problem I choose this one by Maudlin (1995, p.7), which presents it as an incompatibility between three assumptions:

1.A The wave function of a system is complete, i.e., the wave function specifies (directly or indirectly) all of the physical properties of a system.

1.B The wave function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).

1.C Measurements of e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e. at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).

In a nutshell, each of Putnam's favored "realist" approaches proposes to solve the problem by rejecting a different assumption. Bohmians reject 1.A: they maintain that the wave function does not completely specify all of the properties of a system of particles because each particle always has a precise position not specified by the wave function. Collapse theorists following Ghirardi, Rimini and Weber (1986) reject 1.B by postulating a different, nonlinear, dynamical equation for the wave function that differs little from the Schrödinger equation for a single particle but nevertheless results in determinate measurement outcomes because their enormous number effectively guarantees that the particles in the pointer of a measuring device end up described by a wave function that specifies a pointer indicating either up or down and not both. Everettians reject 1.C because they take the final wave function of system plus measuring device to specify that the latter is *both* in a state which indicates spin up *and* in a state which indicates spin down (each in a different "branch" world.) Putnam himself rejects Everettian realism on the grounds that probabilities of measurement outcomes make no sense if one rejects 1.C. He acknowledges that each of the other "realist" options faces difficulties but expresses optimism that these may be overcome by further research.

But, in a pragmatist view, no such research is required since the measurement problem never arises. A pragmatist should reject 1.A not because the wave function of a system specifies its properties incompletely but because the wave function is not in the business of specifying its properties in the first place! The role of the wave function is to provide sound advice on what cognitive attitude to take toward magnitude claims, including claims about the final position of measuring devices' pointers. It can play this role only on the *assumption* that significant magnitude claims have determinate truth values, and that exactly one of each set of mutually incompatible and jointly exhaustive significant claims about the value of a magnitude is true. In particular, any reasonable application of quantum theory to a measuring device requires the assumption that its pointer ends up pointing in *some* direction (and not also another), so of course no wave function can be expected to specify why or even that it does.

Rejection of 1.A as based on a mistaken view of the function of a quantum state suffices to dissolve the measurement problem. But a pragmatist should also reject 1.B for a related reason. It is a presupposition of 1.B that a system's wave function specifies its dynamical evolution in the sense of (at least partially) specifying what physical properties it has at each moment. In that case any discontinuous, nonlinear change in the wave function correctly ascribed to a system implies a change in its physical properties incompatible with the linear dynamical equation that otherwise specifies how these change. But as we shall soon see there are circumstances in which an agent is correct to ascribe a wave function or other mathematical representative of a quantum state to a system that changes discontinuously and nonlinearly while denying that this implies any change in the system's physical properties. This is just what a pragmatist would expect, given his view of the primary role of a quantum state as input to the Born rule. One must sometimes discontinuously change the wave function one ascribes to a system in order correctly to update one's credences in the light of newly acquired information. These correctly updated credences do not concern the system's present physical properties but actual or possible future eventualities involving it.

4. Why there is no quantum non-locality

Many people believe that quantum phenomena manifest what Einstein referred to as "spooky" action at a distance (while dismissing the possibility). Bell's work is often cited in support of this belief, as in the following quote from a recent expository review:

> Bell's theorem asserts that if certain predictions of quantum theory are correct then our world is non-local. (Goldstein *et. al* ((2011), p.1)

Although these predictions have by now been thoroughly verified, their significance warrants the continuing extraordinary efforts by experimental physicists to remove all possible remaining loopholes. In "The Curious Story of Quantum Logic" Hilary makes it clear that he shares this belief:

> Bell's theoretical predictions, predictions which unquestionably follow from quantum mechanics, and have moreover been experimentally confirmed, show that there are causal anomalies that are *observable* without postulating any exhaustive interpretation whatsoever. The phenomena *themselves* are "causally anomalous", in classical terms. The particular anomaly ("nonlocality") is observable at the level of phenomena. (p. 169)

Later he notes his preference for referring to what Reichenbach called an exhaustive interpretation as a coherent realistic interpretation.

Putnam's main point in this paper is that while modifying classical logic remains an extreme option for the scientist, there is no need to resort to it in order to arrive at a realistic interpretation of quantum theory—provided one acknowledges that a tenable realistic interpretation inevitably involves "nonlocality". (And that's why he was wrong to think a realistic interpretation must give up classical logic.) But note that in the quoted passage he makes the stronger claim that "nonlocality" is inherent in the observable phenomena themselves, not just in a coherent realistic interpretation of them. This claim is hard to assess since he does not say exactly what he means by "nonlocality".[9] But on one common understanding of that term a pragmatist view of quantum theory makes it clear why this stronger claim is false. Using quantum theory, we can explain the otherwise puzzling patterns of correlation it correctly predicts without any non-locality as defined by Goldstein *et. al* (2011):

> "Non-local" here means that there exist interactions between events that are too far apart in space and too close together in time for the events to be connected even by signals moving at the speed of light.

This definition connects closely to Bell's own formulation of locality in "La Nouvelle Cuisine", the last of an important series of papers (reprinted in his (2004)). He argued there that any seriously formulated theory meeting a local

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[9] In an earlier paper ("A Philosopher Looks at Quantum Mechanics (Again)") Putnam (p.127) says that "locality" means that in experiments set up to test Bell inequalities the measurement of the spin of particle 1 produces no physical disturbance in particle 2. He adds in a footnote that what the locality-violating "disturbance in particle 2" turns out to be is a statistical matter: the probabilities of outcomes of measurements on particle 2 are altered. I'll show why on a pragmatist view of quantum theory there is no unique probability capable of alteration, hence no disturbance in this sense.

causality condition based on an intuitive conception of local action tailored to the structure of relativistic space-time predicts correlations different from those successfully predicted by quantum theory. Applying this condition to "ordinary quantum mechanics" he concluded that quantum theory is neither locally causal nor embeddable in a locally causal theory.

Bell (2004, p. 239) begins his argument by stating the following intuitive *principle of local causality*:

> The direct causes (and effects) of events are near by, and even the indirect causes (and effects) are no further away than permitted by the velocity of light.

Appropriately, he takes this to be too imprecise to serve as a premise in a mathematical argument, involving as it does the vague notions of cause and effect. Such words as 'cause' and 'effect' will not appear in the formulation of any serious theory. But as he points out elsewhere this does not mean that one cannot investigate the causal structure of a theory:

> I would insist here on the distinction between analyzing various physical theories on the one hand, and philosophising about the unique real world on the other. In this matter of causality it is a great inconvenience that the world is given to us once only. We cannot know what would have happened if something had been different. … Physical theories are more amenable in this respect. We can *calculate* the consequences of changing free elements in a theory, be they only initial conditions, and so explore the causal structure of the theory. (2004, p.101)

Indeed, Bell (2004, p. 239) continues by formulating a local causality condition on physical theories of a certain kind based on his intuitive principle.

> *Local Causality* A theory is said to be locally causal if the probabilities attached to values of local beables in a space-time region 1 are unaltered by specification of values of local beables in a space-like separated region 2, when what happens in the backward light cone of 1 is already sufficiently specified, for example by a full specification of all local beables in a space-time region 3 [a thick space-like slice across the backward light cones of 1, 2 that intersects every future-directed causal curve emerging from the overlap of their backward light cones]. (2004, pp. 239-40)

This local causality condition is a key assumption in his proof of a set of Bell inequalities (the so-called CHSH inequalities) whose experimentally observed violation is correctly predicted by quantum theory.

The standard story as to why the quantum predictions are not constrained by these inequalities is that quantum theory violates *Local Causality*—for example, if the *z*-spin of each of a pair of particles in the singlet state is measured simultaneously in regions 1, 2 then the probability of a device in region 1 indicating "up" is not independent of the outcome registered by a similar device in region 2.

This seems to show several things. First, quantum theory is able to predict the observed phenomena only because it violates *Local Causality*. Second, *no* theory satisfying *Local Causality* is compatible with the observed phenomena. Finally, since *Local Causality* is simply an explication of the intuitive principle of local causality, the observed phenomena show that the world is non-local in that there are pairs of events that are directly causally connected even though they are so far apart that they cannot be connected even by an influence propagating at the speed of light. If that's right then the world is indeed non-local in the sense defined by Goldstein *et. al* (2011).

But the standard story is wrong and these conclusions do not follow. Correctly understood, quantum theory does not violate *Local Causality*, but nor is quantum theory a locally causal theory—the condition of *Local Causality* is simply inapplicable to quantum theory because of the way quantum states and Born probabilities function in that theory.

To apply the condition of *Local Causality* one needs to know what local beables a theory countenances in regions 1-3. The application of quantum theory to this scenario presupposes that magnitude claims about "pointer readings" in regions 1, 2 have determinate truth-values sufficient to register the outcomes of the relevant spin-component measurements in those regions: in that sense, quantum theory acknowledges these pointer readings as local beables even though they are not fundamental local beables postulated by quantum theory. The wave function of the singlet state is not a local beable in quantum theory: it represents no novel physical property or entity but serves the quite different function of advising an agent using quantum theory on the significance and credibility of magnitude claims about the pair of particles to which it is ascribed. Indeed, quantum theory acknowledges no relevant local beables in region 3.

Local Causality presupposes that quantum theory attaches probabilities to values of local beables in regions 1, 2. But quantum theory is not a stochastic theory which attaches a unique probability to a future event. The Born probabilities it supplies are for physically situated agents to adjust their credences in magnitude claims whose truth values they are not in a position to determine. Though objective, Born probabilities are not beables postulated by quantum theory, intended to specify physical propensities. Their function is to guide the beliefs of users of the theory, not to represent physical reality. It is for an agent applying the theory to attach probabilities by applying the Born rule to a quantum state appropriate to that agent's physical (and specifically spatiotemporal) location. Guidance is required only because there are physical limits on the information that is accessible from an agent's physical situation: God has no need of probabilities because he knows everything! Now the structure of relativistic space-time imposes strict limits on accessible information, assuming physical processes propagate only within the future light cone. This means that space-like as well as time-like separated agents face different informational limitations, and so require guidance tailored to their different physical situations.

The Born rule generates advice on the credibility of a magnitude claim good for an agent in a specific physical situation, but only if applied to the correct wave function for one in that situation. A system does not have a wave function, independent of the spatiotemporal situation of an actual or merely hypothetical agent. Sufficiently differently situated agents should use *different* wave functions when assessing the credibility of the same magnitude claim concerning a system. So, whatever the situation of the system to which it is ascribed, every wave function and consequent attachments of Born probabilities must be relativized to the physical situation (and specifically space-time location) of an actual or merely hypothetical user of quantum theory. The wave function does not present a God's eye view of physical reality, or even of objective chance.

Suppose Alice and Bob agreed that when far apart (space-like separated) each would measure the spin of a different spin ½ particle in a pair along a direction selected randomly at the last minute—*a* for Alice, *b* for Bob. They have repeated this many times on many pairs and amassed robust statistics of their outcomes. Suppose also that Alice and Bob agree that each pair of atoms was emitted so that

i) at every moment on Alice's world-line prior to her measurement she was correct to assign the pair a spin singlet wave function, and
ii) at every moment on Bob's world-line prior to his measurement he was correct to assign the pair a spin singlet wave function.

This agreement is not arbitrary: it is justified by their individual and physicists' collective experience with such systems, as manifested in observed statistics confirming the application of the Born rule to these and similar wave functions in a huge variety of circumstances. How do Alice and Bob now explain the patterns of correlation displayed by their measurement outcomes?

They first note that quantum theory gives them no reason to doubt their data. Massive environmental decoherence of the right kind at their detectors renders claims about the outcome of each of their measurements highly significant, thus entitling them confidently to report their observations. And the statistical patterns in that data are just what anyone accepting quantum theory should expect on the basis of the Born rule, as applied to the singlet spin wave function (which each of them was justified in ascribing to each pair prior to his or her measurement).

But by itself this is not enough to constitute an explanation, any more than the falling barometer suffices to explain the storm it gives us reason to expect. What is missing is an account of what those patterns physically depend on.

While the statistics in the data depend counterfactually on the singlet state wave function, this dependence is not *physical* since the wave function is not a physical entity. But conditions in the physical world make this the right wave function for Alice and Bob to ascribe to their particle pairs. These conditions are expressed by true, significant magnitude claims about physical systems involved in the emission of the pairs. The statistical patterns in the data physically depend on these backing conditions. Quantum theory helps Alice and Bob explain the statistical patterns in their data by showing why those patterns were just what they should have expected, given the wave function they justifiably ascribed to the pairs, whether or not they were able to specify the particular physical grounds warranting that ascription.

There are features of the statistics collected by Alice and Bob that remain puzzling. While Alice's relative frequency of up and down outcomes is independent of b and Bob's relative frequency of up and down outcomes is independent of a, the relative frequency of Alice's up and down outcomes is *not* generally independent of Bob's *outcome* for fixed b. Indeed, if one idealizes their results, then if $b=a$ there is a perfect anticorrelation between Alice's and Bob's outcomes—she gets up if and only if he gets down. These dependencies are reflected by the violation of the following condition in a probabilistic model for Alice and Bob's statistics:

$$P_{a,b}(A|B)=P_a(A) \tag{1}$$

where A represents the outcome (up or down) of Alice's measurement of spin along the a direction, and B represents the outcome of Bob's measurement of spin along the b direction.

But (1) seems to be simply a formal expression of (an instance of) *Local Causality* for a theory that acknowledges no local beables in region 3! Doesn't this establish Bell's claim that quantum theory is not a locally causal theory? And isn't that tantamount to admitting that even in this pragmatist view quantum theory reveals a non-local world? I will take these questions in turn and show that the answer to both is "No".

By applying the Born rule to the singlet state Alice, Bob and any other user of quantum theory is warranted in making probabilistic statements concerning the outcome of a measurement of spin component along direction *a* by Alice. One such statement is that $P_a(A)=½$, for arbitrary *a*, whether *A* indicates spin up or spin down: this is true whatever spin component (if any) Bob measures on his particle in the pair. The point of this statement is not to specify the objective propensity of *A* but to guide the credence of any user lacking access to additional information, expressible by magnitude claims. This includes Alice before she makes her measurement.

Now assume without loss of generality that Bob makes his measurement in region 2 earlier in their shared laboratory frame than Alice's measurement in region 1. After Bob has made his measurement, he has access to additional information—its outcome *B*. He is well advised to use this information in forming credences as to Alice's possible outcomes. Quantum theory offers him two equivalent ways of using it. The first way is to apply the Born rule directly to the singlet state wave function to calculate the joint probability $P_{a,b}(A\&B)$ and then to conditionalize on his outcome *B*, giving

$$P_{a,b}(A|B)=P_{a,b}(A\&B)/P_b(B)=1-|<A|B>|^2 \tag{2}$$

Alternatively, he may update the quantum state he ascribes to Alice's particle in the light of his additional information and then apply the Born rule to this updated state, as follows:

$$\rho = \tfrac{1}{2}\mathbf{I} \rightarrow |B>, \quad P'_a(A)=1-|<A|B>|^2 \tag{3}$$

Here the prime indicates this Born probability is calculated using Bob's updated wave function $|B>$, not the reduced state $\tfrac{1}{2}\mathbf{I}$ he correctly assigned to Alice's particle before knowing the outcome of his own measurement.

Bob's second way of proceeding exemplifies the pragmatist view of "wave collapse". This is not a physical process, but a revision in the advice offered to a user of quantum theory when that user gets access to previously inaccessible information. The new information is expressible in the language of magnitude claims which state conditions backing the updated quantum state. Note that in this example these conditions concern not the system to which the state is ascribed

(Alice's particle) but a quite different system. Here as elsewhere a wave function does not represent a physical property (e.g. spin component) of the system to which it is ascribed.

The probability $P_{a,b}(A|B)=1-|<A|B>|^2$ to which Bob is best advised to set his credences on learning his outcome B does not generally equal the probability $P_a(A)=½$: indeed if $a=b$, $P_{a,b}(A|B)=0$. This is a clear violation of (1). Why is it not also a violation of *Local Causality*? For a simple reason: quantum theory does not itself attach a unique probability to each value of A in region 1. Quantum theory yields probabilities to its users by way of the Born rule. In this situation it yields *two* probabilities for outcome A, one conditional on outcome B, the other irrespective of that outcome. Each serves the function of advising a situated agent on credence in A, but that advice is different for differently situated agents in so far as they have access to different information (concerning the outcome B). If Born probabilities were local beables, then at most one of $P_{a,b}(A|B)$, $P_a(A)$ could correctly specify the value of that beable in region 1—presumably $P_{a,b}(A|B)$ would express that objective chance, with $P_a(A)$ best understood epistemically, as representing the best guess of someone like Alice who lacks information relevant to that chance. But in a pragmatist view there is no such thing as *the* probability of A—there is only the correct Born probability of A relative to the situation of an actual or merely hypothetical agent well advised to adopt credence in A equal to that probability.

The case of perfect anticorrelations ($a=b$) should make this particularly clear. After getting outcome B, Bob is certain that Alice will get the opposite outcome, not-B. Doesn't this mean that Alice's outcome not-B was certain as soon as Bob got outcome B, whether Alice knew it or not? No: Alice's outcome is certain given Bob's, just as Bob's outcome is certain given Alice's. These *relative* certainties are independent of the spatio-temporal interval between regions 1 and 2. Quantum theory is a source of good advice to agents on what to believe about events in the (relativistic) space-time in which they are physically situated. It is not a theory that specifies a unique, objective chance for each possible future event, including saying which of these are certain to occur.

It is wrong to conclude that quantum theory violates *Local Causality*: a pragmatist view of quantum theory enables one to see why the condition of *Local Causality* is simply inapplicable to quantum theory. But the patterns of correlation in Alice and Bob's data successfully predicted by quantum theory seem to cry out for a causal explanation, and Bell's theorem rules out an explanation purely in terms of a Reichenbachian common cause that screens off Alice's outcomes and settings from Bob's. This has convinced many that the observations themselves manifest some kind of space-like causal influence or interaction linking events in regions 1 and 2 over and above their connection to events in region 3. Why doesn't the explanation quantum theory offers simply show the world is non-local by revealing the nature of that link?

There was no explicit mention of causation, interaction or influence in the account I gave of how quantum theory helps us explain patterns in Alice and Bob's data that violate Bell inequalities. To draw any conclusions about non-locality one must defend an account of causation/interaction/influence that makes explicit the claimed connection to non-locality. A natural way to do so is in terms of counterfactuals.

Maudlin (2011, p118) makes the following assumption:

(*SC*) ...given a pair of space-like separated events *A* and *B*, if *A* would not have occurred had *B* not occurred even though everything in *A*'s past light cone was the same then there must be superluminal influences. (p. 118)

This may be applied directly to the outcomes of Alice and Bob's measurements on a single pair of particles. Quantum theory itself does not imply the counterfactual in the antecedent of (*SC*). But by mandating maximal credence in the consequent of this counterfactual, conditional on its antecedent, it does the next best thing. In this sense, quantum theory supports that counterfactual: *A* and *B* are indeed counterfactually dependent in this situation. If (*SC*) is true, then it also supports the conclusion that our world is non-local in the sense of Goldstein *et. al* (2011). But the explanation of patterns in their data Alice and Bob can give using quantum theory undermines (*SC*)!

Consistent with that explanation, any superluminal influence would have to link an event in region 1 and an event in region 2. In a pragmatist view, quantum theory acknowledges no beables (local or non-local) capable of connecting distant setting to local outcome, and each of Alice and Bob assign the same Born probability to their own outcome irrespective of their partner's setting. So, any superluminal influence would have to link their outcomes.

Nothing in relativistic space-time breaks the symmetry between the pair of space-like separated regions 1 and 2. Moreover, the explanation Alice gives of their data is symmetrically related to that given by Bob (she takes his outcome counterfactually to depend on hers, while he takes her outcome counterfactually to depend on his). If these counterfactual dependencies correspond to a superluminal influence between their outcomes then this is either mutual or merely relative to their respective situations. While (*SC*) does not use causal terminology explicitly, his surrounding discussion makes clear that Maudlin assumes that any superluminal influence would be causal—indeed, what could be meant by a *noncausal* influence?

So, if there is superluminal influence between Alice's and Bob's outcomes it is either because each is a cause of the other or because relative to Alice's situation her outcome is a cause of Bob's (but not *vice versa*), while relative to Bob's situation his outcome is a cause of Alice's (but not *vice versa*). A perspectival treatment of causation has indeed been advocated by Price (2007) according to which for certain events *e*, *f* whether *e* causes *f* or *vice versa* might be sensitive to extreme differences in the physical situations of a pair of merely hypothetical agents. But Alice's and Bob's situations do not differ in this way. Moreover, Price's perspectival treatment is based on a manipulationist approach to causation along very similar lines to that which I shall use to argue against the view that the counterfactual dependencies acknowledged by Alice and Bob evince superluminal influences.

Goldstein *et. al* (2011) characterize non-locality in terms of an *interaction* between space-like separated events, and this seems the right way to describe some possible mutual causal influence between Alice's and Bob's outcomes, consistent with the symmetries of their situation. But the explanation of their data they are able to give using quantum theory makes no mention of any such influence, and recent work on causation shows there are excellent reasons to resist glossing the counterfactual dependency each acknowledges between their outcomes as causal. In a pragmatist view there is no non-local interaction between these outcomes or between any other space-like separated events involved in violations of Bell inequalities.

A central theme of much recent work on causation and causal modeling by philosophers, computer scientists and a variety of social scientists and medical researchers is that the best way to assess the causal relations obtaining among a set of probabilistically related variables is to ask what would happen under various hypothetical interventions. In an approach like that of Woodward (2003) these are not required to be technically feasible human operations, or even physically possible processes. The idea is that where variables X, Y are probabilistically related then X is a cause of Y only if some intervention that changes the value of X thereby also changes the value of Y, or at least its probability distribution. But if one cannot even make sense of the idea of intervening on X, then X is not a cause of Y.

Can one make sense of the idea of intervening in the outcome of (say) Bob's local measurement, and would any such intervention change the outcome of Alice's distant measurement, or at least its probability distribution? In a pragmatist view of quantum theory, no local action of Alice or Bob could alter either of their outcomes without disrupting the pair of particles concerned (e.g. by preparing a different quantum state). In particular, choosing to measure a different spin component would not have this effect. Quantum theory itself provides no resources on which one can draw to make sense of an intervention capable of changing the outcome of Alice's or Bob's measurement of a fixed component of spin.

In his sophisticated discussion of what the possibility of intervention requires, Woodward (2003, pp. 130-3) argues that an intervention must be conceptually possible, though it need not be physically possible. He considers a case in which an event *C* that is a potential locus of intervention occurs spontaneously in the sense that it has no causes. He argues that even in this case one can make sense of an intervention on *C*. This suggests that one can still make sense of the idea of an intervention that alters the outcome of Bob's measurement. But if one examines Woodward's conditions on an intervention it turns out that if these could all be met here then the acknowledged counterfactual dependencies between these outcomes are not both causal.

Woodward (2003, p. 98) states necessary and sufficient conditions for *I* to be an intervention variable for *X* with respect to *Y*. These include

(I2) *I* acts as a switch for all the other variables that cause *X*. That is, certain values of *I* are such that when *I* attains those values, *X* ceases to depend on the values of other variables that cause *X* and instead depends only on the value taken by *I*.

Suppose some intervention variable *I* could meet this condition with respect to Bob's outcome variable *B*. Either Alice's outcome variable *A* is a cause of *B* or it is not. If it is, then (I2) implies that *I* makes *B* cease to depend on *A*: the value of *A* may be held fixed or freely varied under the intervention *I* that sets the value of *B*. But this hypothetical intervention would show that *B* causes *A* only if it were to change the value of *A*, or at least its probability distribution. If *A* is held fixed under *I* it is obviously not changed by it. But if *A* is varied at will then it *has* no probability distribution, so *I* cannot be said to change the probability distribution of *A*. Hence *A* is not a cause of *B*. So, *I* is an intervention variable for *B* only if *A* is not a cause of *B*. But if there is no possible intervention variable for *B* then *B* is not a cause of *A*. It follows that either *A* is not a cause of *B* or *B* is not a cause of *A*. Consequently, there is no mutual causal interaction between *A* and *B*.[10]

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[10] The symmetry of the situation permits an extension of this argument to establish the stronger conclusion that *neither* of *A* or *B* is a cause of the other.

On an interventionist approach to causation amenable to a pragmatist interpretation of quantum theory, anyone accepting quantum theory should take some physical event backing the assignment of the singlet state as common cause of Alice and Bob's separated outcome events. But she should reject the claim that a local setting is a cause of a distant outcome, since in this case there is not even any counterfactual dependence between these events. She should reject any claim of causal dependence between the outcomes. Finally, she should reject any claim of superluminal influence or interaction. Bell's argument based on local causality establishes no such thing. If you accept quantum theory you have no reason to believe that our world is non-local in any of these senses.

These are important conclusions, but they leave one of Putnam's points unaddressed. More than once in "The Curious Story of Quantum Logic" he notes (with apparent endorsement) Reichenbach's view that for an account to be non-anomalous action-by-contact must be obeyed. I have argued that there is no failure of action-by-contact between any space-like separated events involved in violations of Bell inequalities—because there is no action! But I just acknowledged that something happening in a region time-like or null-separated from regions 1, 2 is a common cause of effects in those regions, while admitting that quantum theory leaves Alice and Bob with nothing to say about what connects this common cause to its effects. One thing notably missing from the explanation of violations of Bell inequalities we can give using quantum theory is an account of any causal processes propagating from events involved in preparing a spin singlet pair to the outcomes of spin-measurements on its particles. Such an account would secure conformity to Bell's *intuitive* principle of local causality. Like Putnam, I would like to see a theory that could either fill that gap or make it clear why it is a mistake to try to do so. Unlike him, I don't see this in quantum theory or likely to emerge from current attempts to square it with scientific realism.

5. What is quantum theory about?

Putnam is quite right when he says

> Obviously, quantum mechanics in its standard form does not wear its beables, local or otherwise, on its sleeve. (p. 153)

A theory's beables are what it says there is in the physical world. If we had an agreed formulation of quantum theory in first order logic, they would be represented by the physical entities in its domain of quantification and the predicates it employs when attributing physical properties and relations to them—its ontology and ideology, in Quine's terminology. I have argued that a wave function denotes no physical entity and does not attribute physical properties: it is not a beable in quantum theory. Since magnitude claims attribute physical properties to physical entities they do speak of beables. But quantum theory itself neither contains nor implies any magnitude claims—it merely advises its users on their content and credibility. So, it does not follow that quantum theory is about the beables spoken of by magnitude claims.

Nevertheless, as Putnam says,

> In the case of "standard" quantum mechanics, there is clearly an entity the theory assumes to exist, namely, the "system". (pp. 151-2)

Quantum theory assumes this in the sense that anyone using the theory ascribes a quantum state to some system or systems. In the case of non-relativistic quantum mechanics, this system often seems clearly physical, as when one ascribes a wave function to an electron or hydrogen atom in order to predict or explain some aspect of its behavior by applying the Born rule to magnitude claims about it. But the status of the system is less clear in other applications. Physicists commonly speak of the quantum mechanics of the simple harmonic oscillator, a two-level system, or the center of mass system of an atom or molecule, and quantum information theorists spend most of their time analyzing systems of qubits. In such cases the immediate focus is on features of an *abstract* system in a quantum model, albeit with an eye to future applications of this model to physical systems.

Currently fundamental forms of quantum theory are relativistic quantum field theories. These assign quantum states to systems of quantum fields, or (in algebraic quantum field theory) to nets of local operator algebras. Based on theories of a system of relativistic quantum fields, the Standard Model of elementary particles has been highly successful. One naturally assumes that these theories are about elementary particles, and that they describe them very accurately. However, this assumption has been all but refuted by powerful recent arguments.[11] Moreover, some of these same arguments apply equally well against a *field* ontology for a system of quantum fields such as those of the Standard Model.[12] What on earth could these theories be about?

The pragmatist has a simple answer. A quantum field theory is about quantum fields! But although its application presupposes the existence of some physical

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[11] Ruetsche (2011) provides an excellent introduction.

[12] See Baker (2009).

system—Wilczek (2015) calls it a quantum fluid—what the theory actually *describes* is not physical: it is an abstract mathematical structure in a quantum model.[13] The function of that model is to offer sound advice to a user of the theory on the content and credibility of magnitude claims attributing physical properties to physical entities that are *not* quantum fields (nor are they quantum fluids). Decoherence of quantum field systems sometimes endows a claim about particles with enough significance to license a user to apply the Born rule in forming beliefs about physical properties of those particles, such as the number, energy or momentum of photons in a cavity. In other circumstances, one may be licensed to form beliefs about (say) the frequency of the *classical* radiation field in a laser, modeled by a quantized electromagnetic field system.

Quantum theory is about quantum systems, quantum states (represented by wave functions and other mathematical entities), quantum "observables" and other operators (including quantum fields), and Born probabilities. There are many true statements about them. These include the statement that the ground state wave function of the hydrogen atom is spherically symmetric and the statement that the Higgs field has a non-zero vacuum expectation value. But since no quantum-theoretic statement speaks of distinctively quantum physical entities or attributes distinctively quantum physical properties, quantum theory introduces no beables of its own. Hydrogen atoms were acknowledged as physically real long before the advent of the theory that enabled us to refer to their quantum states: the Higgs particle recently discovered at CERN is not *described* by the quantum field theories of the Standard Model that offer us good advice as to what to believe about it. Like evil and the number 17, quantum states and probabilities are objectively real but neither physical entities nor physical properties. In *some* (but not other) applications, a quantum state is ascribed to a physically real system such as an atom or electron. Quantum theory provides us with no new terms referring to physical properties of even these systems: but it is a source of wise advice on how to describe them better using terms from other theories or elsewhere. Quantum

[13] Putnam (p.57 fn.12, p.64) refers to a physics paper as providing an example of conceptual relativity. He claims this provides two equivalent descriptions of the same physical reality (a system of particles) whose mind-independently real condition can be represented in each of these perfectly intertranslatable ways, despite their different ontologies. But what these two ways actually represent is a system of quantum fields in two dimensions—one representing the fields as fermionic, the other as bosonic. This shows nothing about *physical* ontology or ideology since quantum fields are here represented as mathematical structures in models that do not depict particles—neither as bosons nor as fermions.

theory implies no new statements about the physical world: but by helping us to improve our beliefs about the physical world it enables us vastly to increase our abilities to predict, control and explain what happens in it.

6. What about scientific realism?

While stressing that he has always been a scientific realist, Putnam (2012, p.53) reiterates a formulation of that view he gave in 1976. He began there by saying "In one way of conceiving it, realism is an empirical theory" before presenting his famous "no miracle" argument taking the success of science and the preservation of reference under scientific theory change as evidence for scientific realism. A footnote (p.55) endorses a formulation of Boyd as influencing this conception of scientific realism—that terms in a mature science typically refer, and theories accepted in a mature science are typically approximately true. The realist explanation of these features of science (success and reference preservation) is that scientists mirror the world—in the sense of constructing symbolic representations of their environment—and that science succeeds in the way it does because these symbolic representations become increasingly accurate as science progresses.

In a pragmatist view, what is distinctive about the success of quantum theory is precisely that it is *not* due to introduction of new symbols (for beables) permitting us to represent novel structures in the physical world. Quantum theory introduces terms like 'quantum state' and 'quantum field' with a different function in quantum models. They are not intended to mirror the physical world but to guide scientists and other situated agents in better deploying representational resources they already have or are engaged in developing.

One can try to reconcile this view of quantum theory with Boyd-Putnam scientific realism by noting that

i) when applying quantum theory scientists still talk about the same physical entities (atoms, electrons, etc.) and ascribe them the same physical properties (mass, charge, energy, etc.) as before, so the reference of our terms has been preserved through the quantum revolution, and
ii) applications of quantum theory have improved the ways we are able to use these terms to refer, both by increasing our abilities to predict, control and explain natural phenomena and by advising us in what environmental contexts we can use these symbols to make significant claims about physical entities and properties

iii) Boyd-Putnam scientific realism already acknowledged exceptions to the typically referential role of theoretical terms (Putnam (p. 149) notes Bell's disqualification from local beable status of "non-physical" electromagnetic potentials).

But that would be to miss the point that even if an important long-term scientific aim is improved symbolic representation of the physical world, science may at times progress faster by introducing terms *without* that representational function. Language and other symbolic systems provide scientists and the rest of us with wonderful tools for achieving our goals. But these tools don't always function in the same way. Perhaps the central pragmatist moral of quantum theory is that scientists may find new ways of furthering long-term scientific realist aspirations by creating theories whose key terms do not function as representations of physical reality.

7. A quantum challenge to metaphysical realism

Hilary Putnam was always a scientific realist, but his views on metaphysical realism evolved over the years in ways charted in several essays in his (2012). I recently learned of an argument that quantum theory challenges a particular kind of metaphysical realism. I am sorry not to have had the opportunity to discuss this argument with Hilary. I think he would have loved the argument; because of the challenge it presents to that kind of metaphysical realism; and because it would have provoked him further to refine or even modify *his* kind of metaphysical realism.

Realists may disagree about whether wave functions represent something physically real, whether electrons have precise momenta and positions, and whether the world is non-local. But on one point they (nearly!) all agree: quantum measurements have physically real outcomes whose statistics are correctly predicted by quantum theory. The argument seeks to show that this assumption is inconsistent with the universal applicability of quantum theory itself. There is no space here to present it in full detail (see Frauchiger and Renner, 2016) so I will give an informal sketch of a simpler version I heard from Matthew Pusey.

Consider the following (completely practically unrealizable!) thought-experiment. Suppose that Alice and Bob decide to conduct measurements of various polarization components on a large number of pairs of photons, where each pair is assigned the same entangled state. Being lazy, they do not at first perform any measurements themselves, but delegate that task to their friends, Ann and Bill, each of whom performs the required measurements in his or her otherwise completely physically isolated laboratory. For each pair of photons, Ann measures polarization of one photon with respect to axis a_1 while Bill measures polarization of the other photon with respect to axis b_1. By assumption, each of their measurements has a physically real outcome (as registered in their notebooks or stored in their computers): and quantum theory correctly predicts the correlations between these outcomes from the joint probability distribution $P(a_1, b_1)$ calculated by application of its Born rule to the entangled state assigned to the pairs.

After each photon pair is measured by Ann and Bill, Alice and Bob bestir themselves. Instead of asking Ann and Bill what outcomes they observed, they apply very carefully tailored interactions to the entire contents of each of their laboratories (including Ann and Bill themselves inside their labs). They do this repeatedly, for each photon pair independently. Quantum theory then predicts that the effect of these interactions is to restore each photon pair to its original entangled state and to restore each lab + occupant to its state prior to the polarization measurement. Finally, Alice measures polarization of one photon in each pair with respect to axis a_2 while Bob measures polarization of the other photon with respect to axis b_2.

By assumption, each of Alice's and Bob's measurements also has a physically real outcome (as registered in their notebooks or stored in their computers): and quantum theory correctly predicts the correlations between these outcomes from the joint probability distribution $P(a_2, b_2)$ calculated by application of its Born rule to the same entangled state assigned to the pairs. Given our working assumption, quantum theory also correctly predicts the correlations between Ann's outcomes and Bob's from the probability distribution $P(a_1, b_2)$, and between Bill's outcomes and Alice's from the probability distribution $P(a_2, b_1)$, each of which may again be calculated by applying the Born rule to the same entangled state assigned to the pairs.

If the entangled photon state and the axes a_1, a_2, b_1, b_2 are chosen appropriately, the probabilistic correlations predicted in this way by quantum theory will violate a Bell inequality (the so-called CHSH inequality). But since they constitute a joint distribution over all four measured variables the statistics of these assumed real outcomes will always conform to that inequality. We have a contradiction. So, the assumption is false: quantum measurements *do not* always have physically real outcomes whose statistics are correctly predicted by quantum theory. But predictions of quantum theory have always been confirmed by the statistics of measurement outcomes. So, we cannot assume that these measurement outcomes are always physically real!

Some (quantum Bayesians—see my (2016)) deny the objectivity of measurement outcomes, maintaining that any outcome remains essentially personal to the agent who provokes it through his or her actions on the world. Carlo Rovelli

(1996) takes every statement describing the outcome of a measurement to be relational rather than absolute: it expresses just a relation between the measured system and another quantum system that interacted with it.

In my (2017) view a quantum measurement has an objective physical outcome, and a statement about that outcome has a determinate, non-relational, mind-independent truth-value. But acceptance of quantum theory modifies the *content* of the statement by restricting what inferences may legitimately made from its truth. That content is a function of the physical environment of the system concerned. In all practically realizable circumstances the environmental context involves massive decoherence of the system's quantum state, so that all physical observer-systems (not only human agents like Alice, Bob and friends) may legitimately attribute an essentially "classical" content to a statement about any measurement outcome in that environment. But in the (completely practically unrealizable) circumstances described in the thought-experiment this is not so, since Alice, Bob and friends do not share a single environmental context. In that situation they (and we) may continue to agree that there are true statements about their physical measurement outcomes with objective, mind-independent content. But that content does not license reliable inferences between different environmental contexts.

Decoherence confined to each of their individual laboratories supplies the environmental context underlying the content of each claim about the outcome of a measurement in that lab. For Ann and Bill physically to have exchanged information they would have had to join their environmental contexts to form a unified context into which their statements about their outcomes may be reliably exported. Alternatively, either Ann or Bill might have physically exchanged information with Alice or Bob without first exchanging information with each other, permitting each reliably to export statements about his or her outcomes into that different context. The upshot is that while each statement about the outcomes of measurements on each of an entangled pair of photons has objective and essentially "classical" content within an environmental context, there is no such context in which a statement about the outcomes of two measurements on a single photon has well-defined content.

What are the implications for metaphysical realism? Consider the sentence S_n:

The nth photon was recorded as vertically polarized with respect to the a_1 axis.

Suppose Ann makes a statement asserting something by uttering S_n as a sincere report of the outcome of one of her measurements on a photon from the entangled pair. Then

1. This statement is true.
2. This statement cannot be verified by anyone (including Ann) after Alice and Bob have made their measurements on this photon pair: all traces of this outcome (including Ann's memories) have been completely erased by their interventions.

Putnam (2012, p. 68) would add

3. To assert that S_n is true is to assert the same thing as S_n.

Suppose that Alice now makes a statement asserting something by uttering the sentence S^*_n as a sincere report of the outcome of one of her measurements on a photon from the *n*th entangled pair.

S^*_n: *The nth photon was recorded as vertically polarized with respect to the* a_2 *axis*

Then

4. This statement is true.
5. While Alice and Bob can verify S^*_n, no-one can verify both S_n and S^*_n.

Putnam (2012, p. 68) would add

6. To assert that S^*_n is true is to assert the same thing as S^*_n.

(1) - (6) all apparently accord with the metaphysical realism espoused by Putnam in (2012). But then on page 69 we find:

> "to say, as I do, that when we describe things, in Sellars's 'broadest possible sense of the term,' we are *answerable* to those things, and that when we describe them correctly, there is an aspect of reality that is as we assert it to be, is to be a realist in one's view of 'how things, in the broadest possible sense of the term, hang together.'"

and on page 88:

> "On an externalist-functionalist story, for either our beliefs or the proto-beliefs of animals and prelinguistic children to have content is just for them to function as representations of external states of affairs."

I would have liked to ask Hilary whether the contextual account of truth and the environment-sensitive account of content I take to be involved in accepting quantum theory accord with his kind of realism. Sadly, I will never get the chance to do so. We philosophers must carry on without his unique combination of brilliant insights and good sense.

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