The Quantum Mechanical Frame of Reference

Part 1: QBism and Psi-Ontology

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Abstract: QBism explicitly takes the subjective view: probabilities of events are defined solely by past experiences, i.e. the record of observations. As shown by the authors (Fuchs et al, 2013), this: "... removes the paradoxes, conundra, and pseudo-problems that have plagued quantum foundations for the past nine decades". It is criticised for its lack of ontology and anthropocentric nature. However, if Everett's (1957) formulation is taken at face value, exactly the features of QBism are the result, and the ontology is inherent. The anthropocentric nature of the solution is simply an indication that the quantum state is relative, as is central to Everett. Problems of measurement and locality do not arise.

As described by Tegmark (1997), Everett defines the relationship between two fundamentally different views of the world, different types of frame of reference. The outside view is defined by the unitary wave function, the inside view by the record of observations. As Lockwood (1989) states, the preferred basis problem is fully resolved if the latter is taken as the basis. Taken literally, only that defined by the record of observations is determinate in the physical world of this inside view. The reality of QBism is the result. The same can be derived from first principles in the no-collapse universe. Taking the outside view to define all possible decoherent quasi-classical worlds, the physical world of the inside view is the superposition of all such worlds in which it is instantiated. In this quantum mechanical frame of reference only that observed is determinate.

The quantum state as ontology is questioned because it defines only the linear dynamics and cannot account for collapse. No deeper reality is required, however: the inside view, and the collapse dynamics that operates in this type of frame of reference, are emergent properties of the system, and operate at a different level of logical type. The world operates as described by QBism, but is nonetheless defined by the quantum state.

1 Introduction

Since the linear dynamics of the wave function must be supplemented, revised or possibly transcended, in order to account for collapse, it has seemed it may not be fundamental. Additionally, although decoherence gives rise to the appearance of a determinate version of events at a local level, no consensus can be found on a complete, precise, self-contained definition of the world (Saunders, 2010). However, as shown by Lockwood (1989, ch. 13), if the inside view, the frame of reference of the perceiving subject, is taken to be the preferred basis, this problem is resolved. The world is defined precisely, though in a counter-intuitive manner: only where observed. This is the world of QBism (Fuchs et al., 2010). Naturally, these concepts would be more convincing given an ontology. This is provided by taking Everett (1957) at face value.

As stated by Greaves, his formulation must surely form the basis of any successful definition, since his is the only solution that fits naturally with special relativity, and the formalism is retained in its pure and simple form:

> This is the ‘conservative’ solution, in the sense that it is the only solution that retains the existing physics (quantum state and unitary evolution) without amendment or addition. (2004, p. 1)

The problem with Everett's formulation is that a key explanatory principle is missing. As he states in his conclusion, the state of the memory, defined as the record of observations, has very different properties to the physical reality:

> When interaction occurs, the result of the evolution in time is a superposition of states, each element of which assigns a different state to the memory of the observer. Judged by the state of the memory … pure Process 2 wave mechanics, without any initial probability assertions, leads to all the probability concepts of the familiar formalism. (1957, p. 462)

In other words, while the physical world is a superposition of states, the state of the memory is specifically defined; hence there is the appearance of collapse. However, no explanation of why or how is given.

There is no physical collapse. As shown by Barrett's (1999) exhaustive analysis, this is the central problem with acceptance of his formulation: it has not been possible to explain the production of a single and specific determinate record of observations, instantiated in physical reality. Decoherence explains the appearance of collapse, but cannot form a complete resolution. As stated by Bacciagaluppi, it is part of the folklore of decoherence that it provides the complete answer to why macroscopic objects in fact appear to us to be in localised states:

> As pointed out by many authors, however (recently e.g., Adler 2003; Zeh 1995, pp. 14-15), this claim is not tenable. (2012)

The situation is clarified by Tegmark, stating it is crucial we distinguish between:

- the *outside view* of the world (the way a mathematician thinks of it, *i.e.*, as an evolving wavefunction), and
- the *inside view*, the way it is perceived from the subjective ... perspective of an observer in it.

(1997, p. 2; emphasis in original)

In quantum mechanics, the outside view is the universe of all possibilities, defined by the unitary wave function, while the inside view is one specific version of reality, defined by the record of observations. These different views of existence are two completely different kinds of frame of reference. They exist at different levels of logical type, as shown by the following intuitive argument.

The no-collapse universe of the unitary wave function must contain, in some form, all possible physical worlds. Thus, irrespective of whether we can define such worlds with precision, a specific record of observations, a structure of information, is multiply instantiated: there are many, slightly different versions of a decoherent quasi-classical world in which this version of the inside view exists. Since all are coincident and superimposed, the net result is one single structure of information. As a result, this is simultaneously the inside view of all of the physical worlds containing this inside view; and the physical environment of this inside view is the effective superposition of all these worlds, here the quantum mechanical frame of reference.

This frame of reference gives rise to exactly the principles inherent in Lockwood's interpretation, and explicitly described in QBism. The observations recorded are defined only to the level of resolution of the sensory data. Nonetheless, these observations comprise the only definition of the quantum state of the world of the individual.[1] In this frame of reference, therefore, the probabilities of future events are defined solely by this record of observations. Thus the world of QBism has a physical definition and an ontology. Naturally, in this context there is no measurement problem: change of the record of observations changes the definition of the set of worlds in which the inside view exists, and thus the quantum mechanical frame of reference.

It may seem highly unsatisfactory that the real physical world is defined solely by the record of observations, a structure of information. However, as stated by Wheeler: "... it is not unreasonable to imagine that information sits at the core of physics" (1998, p. 340). This makes perfect sense once it is noted that only on the inside view is this the case. The physical world of the inside view, being defined by a *set* of physical environments, is of different logical type to that of the outside view. It is at this different level of logical type that the world, meaning the effective physical environment of the inside view, is defined by, and only by, the record of observations.

It is in order to emphasise the radically different nature of this domain from the standard concept of quantum state that the term quantum mechanical frame of

1 As described in Section 3, the term observer is reserved for the physical entity.

reference is adopted here: collapse takes place only at this level of logical type. It is primarily an information process: the addition of the observation to the record of observations changes the quantum mechanical frame of reference.

Problems of measurement, locality and ontology are naturally resolved. As is clear from Everett's statement quoted above, the state of the memory is the central component of the theory. It is judged by the state of the memory, the inside view, that collapse occurs. This is the quantum jump, and it is a phenomenon contextual to the linear dynamics. This is the jump from one quantum state to another; and this is possible only at the higher level of logical type: change of perspective on a system can only be registered, let alone enacted, at a higher level of logical type than the definition of the system, in this case the quantum state.

After the better part of a century of discussion, it seems clear there is no outside-view explanation of collapse. It is an inside-view-only phenomenon. As Everett states:

> ... it develops that the probabilistic aspects of Process 1 reappear at the subjective level, as relative phenomena to observers. (1973, p. 115)

However, despite enacting a dynamics impossible at the level of physical reality, this is an emergent process rather than a more primary one. There is no need to consider the quantum state defined by the wave function as anything other than fundamental. There is nothing 'deeper'. The existing physics of quantum mechanics is complete, and accounts for both linear and collapse dynamics as held by Everett. Moreover, on both inside and outside views there is complete knowledge about the physical state of the system. Psi-ontology rules.

2 The World Hologram

The inside view of the world implicit in Everett's formulation is the perceptual reality, defined by the record of observations. The nature of this structure of information is now well understood. It is a virtual reality representing the physical world observed:

> What we experience directly is a virtual-reality rendering, conveniently generated for us by our unconscious minds from sensory data (Deutsch, 1997, p. 120)
>
> Our brain constructs a three-dimensional model. It is a virtual reality in the head. (Dawkins , 1998, p. 276)
>
> Every last scrap of our external experience is of virtual reality. (Deutsch, 2011, p. 10).

As is logically obvious but intuitively elusive, what is actually experienced is the virtu-al-reality rendering of what physical reality looks like, sounds like etc., rather than the physical reality itself. This is the perceptual reality, the inside view.

This neural activity is not experienced as such, but forms a field of information mentally projected out into space, seeming to be 'out there'. As Deutsch goes on:

> Consider the nerve signals reaching our brains from our sense organs. Far from providing direct or untainted access to reality, even they themselves are never experienced for what they really are – namely crackles of electrical activity. Nor, for the most part, do we experience them as being where they really are – inside our brains. Instead, we place them in the reality beyond. We do not just see blue: we see a blue sky up there, far away. We do not just feel pain: we experience a headache, or a stomach ache. The brain attaches those interpretations – 'head', 'stomach' and 'up there' – to events that are in fact within the brain itself. (p. 10)

The net effect is exactly like a hologram. The virtual-reality rendering of the world is experienced as a three-dimensional field of information that is mentally projected out onto the real three-dimensional physical world to coincide precisely. This is here referred to as the world hologram. In terms of cybernetics, the world hologram is simply the navigation equipment of the body-mind system; but in regard to quantum mechanics this structure of information takes on a remarkable significance. It is the spatially distributed representation of the state of the memory in Everett's scheme. The human neural system represents the state of the memory, the integrated synthesis of the observations recorded, as the world hologram.

3 The Inside View

Everett defines physical observers as:

> ... automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine configurations. (1957, p. 457)

The integrated synthesis of the sensory data forms the world hologram. The integrated synthesis of the observations of machine configuration forms the self-concept avatar, the representation of the observer at the centre of the world hologram. The term individual is here used for the person on the inside view, identified with the self-concept avatar. The nature of this individual is described in Part 2. The term observer is reserved for the physical entity, the body-mind that produces the inside view. This is the distinction Everett makes rather obscurely, and only in a footnote:

> In this situation we shall use the singular when we wish to emphasize that a single physical system is involved, and the plural when we wish to emphasize the different experiences for the separate elements of the superposition.

> (e.g., "The observer performs an observation of the quantity A, after which each of the observers of the resulting superposition has perceived an eigenvalue.") (1973, p. 68n)

This is a crucial distinction. With respect to the observer, the physical entity in the physical world, all possible versions of events take place. With respect to observers plural, the different experiences, here the individuals, only one specific version of events happens. The latter are the different, discrete, inside views.

Why should there be this difference? While decoherence is not ruled out as the answer, Lockwood (1989, p. 234) provides a principle that resolves the issue at a fundamental level. He states that phenomenal perspectives are discrete even when the physical domains that instantiate them are superposed. He defines a phenomenal perspective as the total content of a given state of awareness; an extended quote is given in the Appendix. The question then arises, why should the phenomenal perspective have this special property? It seems this is simply a property of information. Just as in a quantum computer, where a computation can proceed with respect to each separate structure of information, within the context of a superposition, each separate phenomenal perspective has a separate operational existence. Since quantum computation is known to operate in practice, this principle must apply. In this case, the experiences are functionally discrete even though the physical instantiations in the brain producing them are superposed.

4 The Centred World

This distinction offers a solution to the preferred basis problem, which has shown so intractable when a solution in physical reality is sought. As stated by Barrett:

> Making the total angular momentum of all the sheep in Austria determinate by choosing such a preferred basis to tell us when worlds split, would presumably do little to account for the determinate memory I have concerning what I just typed. But this is the problem, we do not really know what basis would make our most immediately accessible physical records, those records that determine our experiences and beliefs, determinate in every world. (1998)

It seems that no ordinary physical basis can be made to work. Lockwood proposes that what is preferred:

> … is preferred only from the point of view of awareness itself: from a point of view that has phenomenal perspectives as its windows on reality. (1989, p. 236)

This of course solves the problem. With respect to the individual on the inside view there is no question that the records that determine our experiences and beliefs are

determinate in every world. As Everett states, in the simple case of a single observation, the final result is a superposition:

> However, in each *element* of the superposition … the object-system state is a particular eigenstate of the observation, and *furthermore the observer-system state describes the observer as definitely perceiving that particular system state.* This correlation is what allows one to maintain the interpretation that a measurement has been performed. (1957, p. 459; emphasis in original)

Here the word observer is referring to the individual i.e. the inside view. The physical brain is in a state of superposition, but within that superposition, each different version of the inside view is correlated with a different, specific, version of the physical world. However, the question remains of why this should be the preferred basis in operation.

The record of observations is certainly highly significant, being the definition of the correlations of the individual with the physical world, thus defining what must be determinate: it is the record of observables defining the set of commuting operators which define the determinacy of the observed system, Everett's relative state. Taking his theory literally, this world is defined solely by the record of observations, and reality at large is indeterminate. As Lockwood (1989, p. 234) states:

> On [the relative state] view there is no state vector reduction, and objects do, in general, exist in superpositions of eigenstates of macroscopic observables.

As Everett concludes: “There is no definite position for our macroscopic cannonball!” (1973, p. 61). If there is no state vector reduction, and the preferred basis is the phenomenal perspective, only that defined by the observation is determinate on the inside view, and all else is indeterminate. This is a type of centred world as defined by Vaidman, one:

> ... centered on a perceptual state of a sentient being … In this world, all objects which the sentient being perceives have definite states, but objects that are not under her observation might be in a superposition of different (classical) states. (2008)

This is the description of the world arrived at by QBism. Since only what is observed is determinate, probabilities are defined solely by the record of observations; and individuals live in different, idiosyncratic versions of the world.

The idea that objects in general should effectively exist in a state of superposition is a radical departure from the established worldview, and appears directly in contradiction to the concept of decoherence which is widely held to give the appearance of collapse in all ordinary macroscopic situations. However, there is an outside-view argument that comes to the same conclusion, taking decoherence into account. Ascribing a fully physical actuality to the wave function, the universe seems best described as a multiverse in which the wave function defines decoherent quasi-

classical worlds, each akin to the conventional concept of a space-time array of solid, determinate, physical entities. As Tegmark states, on the outside view:

> ... Everett's multiverse is simple. There is only one wavefunction, and it evolves smoothly and deterministically over time without any kind of splitting or parallelism. The abstract quantum world described by this evolving wavefunction contains within it a vast number of classical parallel storylines ("worlds"), continuously splitting and merging, as well as a number of quantum phenomena that lack a classical description. (2007, p. 3)

In this context, a specific inside view is multiply instantiated. Identical observation records place all the multiple instantiations at the same location in space-time, thus all instantiations are coincident as well as superimposed. With respect to the world hologram, a structure of information, the result is a single structure of information. In other words, there is only one instance of a specific phenomenal perspective.

A specific inside view, defined by a specific instance of the world hologram, is of course the inside view of all of the quasi-classical worlds in which it is instantiated. Here it is proposed that this is literally the case in reality. In other words, in the frame of reference of the individual on the inside view, the physical world is the superposed sum of all these quasi-classical worlds. One could argue that in each world this structure of information is experienced by a different version of the physical observer. However, as described in Part 2, this view is untenable. Thus the experience of a specific inside view is simultaneously the experience of the superposed sum of all the versions of the world in which it is instantiated.

In this frame of reference, everything not observed is indeterminate because every possible different variation of objects and events is included in the superposed sum. Conversely, everything observed is determinate because it is, by definition, identically the same in all versions of the world in the superposition. Thus the world is exactly as held in QBism: defined only where experienced and observed. Here, however, we have a physical explanation and thus an ontology for this type of interpretation.

The determinacy of this world is defined solely by the record of observations, a structure of information. Nonetheless, this is a real physical world defined by a specific quantum state, the quantum mechanical frame of reference. This perspective also naturally resolves the longstanding paradox of Schrödinger's Cat (1935). In the centred world of the scientist, there really is a superposition of dead and alive cat in the box, while, of course, with respect to the world of the cat, in different versions of those superposed worlds in which the scientist exists, it is either alive or dead. Before the scientist makes the crucial observation, he is defined as existing in all the worlds containing the box, half of which have in them a live cat, and half a dead one. On making the observation of the state of the cat, he is thereby defined as existing in just one half of those worlds, corresponding to a specific state of health of the cat.

5 Logical Type

The radical difference between inside and outside views is clearly illustrated by the concept of logical type and the way in which this dissolves the measurement problem. The measurement problem arises because the linear and collapse dynamics are incompatible. As Barrett states:

> … if one supposes that measuring devices are ordinary physical systems just like any other, constructed of fundamental particles interacting in their usual determinate way (and why wouldn't they be?), then the standard theory is logically inconsistent since no system can obey both the deterministic and stochastic dynamics simultaneously. This is the measurement problem. (1999, p. 15)

However, the dynamics operate in the different contexts of inside and outside views; and just as the definition of these frames of reference is of different logical type, so too is the operation of their respective dynamics.

Logical type (Russell, 1908) is the distinction between a set and the members or elements of that set. The inside view is a phenomenon of a different logical type to the outside view because the physical world of the inside view is defined by the set of all possible versions of a quasi-classical world which instantiate this world hologram: the quantum mechanical frame of reference is a second-logical-type phenomenon.

This is what explains the appearance of collapse. On the inside view, collapse occurs on observation because the addition of an observation to the world hologram alters the set of quasi-classical worlds in which the individual is defined as existing. This is what is hidden at the core of Everett's formulation. It is “Judged by the state of the memory” (ibid) that collapse occurs because this is what defines the determinacy of the physical reality of the individual on the inside view: it is defined by the superposition of all of the versions of the world in which this inside view is instantiated. This is the quantum mechanical frame of reference; and it is defined solely by the record of observations. It is important to note, however, that this is not a causal phenomenon, but one of emergence. The physical does not of course change, only the view of the physical.

This is what makes sense of Everett's formulation and the appearance of collapse he describes. On the making of an observation the frame of reference changes: the quantum mechanical frame of reference is redefined, and the individual is now defined as existing in all possible quasi-classical worlds in which this observation has determinately taken place. In effect, on the inside view, there is change of the quantum state on the making of each observation. This is the explanation of the appearance of collapse, and events taking place, encountered by all individuals.

On the outside view, there is no collapse. The measurement instruments, including the perceptual apparatus of the observer, are of course made of the same stuff as that

which is observed. All are physical entities, subject to the linear dynamics. This is the simple logic of the outside view defined by the equations. On this view, the making of a measurement necessarily results in a superposition of states, each element of which assigns a different state to the measuring device. As stated by Everett:

> Throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique *state* of the observer (which follows from the representations of interacting systems). Nevertheless, there is a representation in terms of a *superposition*, each element of which contains a definite observer state and a corresponding system state. Thus with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the *corresponding* eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations. (1957, p. 459; emphasis in original)

Here the term observer state clearly refers to the definition of the individual on the inside view. Each branch represents a different version of the inside view; and the corresponding system state in each instance is the quantum mechanical frame of reference of the individual, Everett's relative state. On each inside view, effectively, there has been a collapse to a specific version of the outcome. The addition of the observation to the record of observations has resulted in change of the definition of the inside view, corresponding to a different quantum mechanical frame of reference.

The two dynamics operate at the two different levels of logical type. The linear dynamics of the wave function operates only on the outside view: no change occurs on the inside view in-between the making of observations. Collapse occurs only on the inside view; it is an emergent, second-logical-type phenomenon. There is no such process on the outside view. As shown in Barrett (ibid) no such change is possible at the level of the wave function, however interpreted. This can only occur at a different level of logical type.

There is, of course, no change to the physical world on the making of an observation. It is simply that the frame of reference of the inside view moves from one quantum state, one quantum mechanical frame of reference, to another. As stated by Everett:

> *... it is not so much the system which is affected by an observation as the observer, who becomes correlated to the system*. (1973, p. 116; emphasis in original)

More precisely, with the making of each observation, each individual in the observer system is redefined, as having made that observation, and is thus correlated with a different version of the world, one in which that observation, and only that observation, has been determinately made.

6 QBism

The world of QBism is the simply the reality of the inside view. The forgoing explains the reality of Qbism's most radical concept. As stated by Fuchs et al.:

> What is real for an agent rests entirely on what that agent experiences (2013, p. 3)

Given that only what has been directly experienced and observed is determinate, this is directly implied. Furthermore, the observations made are defined only to the resolution of the sensory apparatus of the observer. Thus for the observation of any given macroscopic object, the set of all possible worlds in which this observation is made by this observer, includes every possible microscopic definition of this object. The net result on the inside view is that only that much of the physical environment defined by the record of observations, in terms of sensory experience, is determinate.

The central tenet of QBism follows automatically. In most situations in an ordinary world, such as is currently maintained in the prevailing worldview, the subjective assessment of probability is just a best guess because the information available about complex situations is not complete. The real probability would be defined by the physical reality in all its determinate detail. In a centred world, however, the quantum mechanical definition of probabilities of future events is defined solely by the record of observations. Thus the data used in the subjective assessment of probabilities is the same information as defines the quantum mechanical world itself. In other words, subjective probability is the same as objective probability.

This definition of the world is not some ephemeral abstraction; it is expressed as the superposed sum of all of the worlds instantiating the record of observations. In this context, problems of the interpretation of probability are also naturally resolved. Taking the many versions of a determinate quasi-classical world as real phenomena, probability can be seen as an objective fact on the inside view. This is essentially the counting worlds approach of Deutsch (1999) and Żurek (2005), but here the measures of existence of all quasi-classical worlds are taken to be equal. When a fair coin is tossed, given the very large number of worlds in the superposition, the percentage of worlds with each outcome must necessarily be represented precisely by the standard numerical probability of each outcome: one half. When an observation of the result is made, the individual will thereby be defined as existing in only those worlds, one half of the total number, in which that specific result was the case. This is graphically illustrated in Lockwood's scheme (1989, p. 231).

This provides a straightforward answer to the question posed by Saunders: “Why should subjective probability track chance?” (2004, p. 2). His 'principal principle', that it should do so, is inherent.

7 Non-locality

With regard to non-locality, the centred world eliminates the problem. As Smerlak & Rovelli explain in *Relational EPR* (2006), EPR-type correlations do not entail any form of non-locality when viewed in the context of relational quantum mechanics. When observer *A* makes an EPR-type measurement, any observer *B* at a remote location making the corresponding measurement must theoretically get the correlated result, with no time delay. However, as they point out, Einstein's ingenious counterfactual argument fails because it works under the assumption of a classical world (α is *A*'s system and β is *B*'s):

> *... it is the assumption that B is classical and fails to obey quantum theory that creates EPR non-locality*.
>
> But all systems are quantum: there are no intrinsically classical systems. Hence the hypothesis that *B* does not obey quantum theory is physically incorrect. It is this mistaken hypothesis that causes the apparent violation of locality.
>
> In other words, in the sequence of events which is real for *A* there is no definite quantum event regarding β at time t_0, and therefore no element of reality generated non-locally at time t_0 in the location where *B* is. Hence Einstein's argument cannot even begin to be formulated.
>
> What changes instantaneously at time t_0, for *A*, is not the objective state of β, but only its (subjective) relative state, that codes the information that *A* has about β. This change is unproblematic, for the same reason for which my information about China changes discontinuously any time I read an article about China in the newspaper. Relative to *A*, β is not affected by this change because there is no β-event happening at time t_0. The meaning of the sudden change in the state of β is that, as a consequence of her measurement on α, *A* can predict outcomes of *future* measurement that *A* herself might do on β, or on *B*. (2006, p. 6; emphasis in original)

In a centred world, as in relational quantum mechanics, the quantum state is defined only with respect to observations made by *A*, thus the argument given applies.

This latter point makes sense of the apparently surreal implication that individuals live in different versions of the physical world. As stated by Fuchs et. al.:

> This means that reality differs from one agent to another. This is not as strange as it may sound. What is real for an agent rests entirely on what that agent experiences, and different agents have different experiences. (2013, p. 3)

As stated by Mermin:

> This is, of course, nothing but the famous story of Wigner and his friend, but in QBism Wigner's Friend is transformed from a paradox to a fundamental parable. (2014, p. 10)

8 Relative State Reality

Objections have been raised to QBism stating that it is anthropocentric. However, this is taken to be a fundamental feature of quantum mechanics in the well-known concept of Wigner's friend (1961). The phenomenon is explained in some detail by Laudisa & Rovelli; their treatment addresses two measuring systems, (*O′*) corresponding here to Wigner, and (*O*) to his friend, and an observed system (*S*):

> What appears with respect to *O* as a measurement of the variable *q* (with a specific outcome), appears with respect to *O′* simply as the establishing of a *correlation* between *S* and *O* (without any specific outcome). As far as the observer *O* is concerned, a quantum event has happened and a property *q* of a system *S* has taken a certain value. As far as the second observer *O′* is concerned, the only relevant element of reality is that a correlation is established between *S* and *O*. This correlation will manifest itself only in any further observation that *O′* would perform on the *S*+*O* system. Up to the time in which it physically interacts with *S*+*O*, the system *O′* has no access to the actual outcomes of the measurements performed by *O* on *S* . This actual outcome is real only with respect to *O* (2005)

This is a natural consequence of centred worlds. Say Wigner's friend is Schrödinger, observing the state of the eponymous cat. In Wigner's world, not only the state of the cat, but which version of the outcome his friend observed, and which version of events he followed next, are all indeterminate because he is defined as existing in all possible quasi-classical worlds in which his friend carried out the experiment.

Unlike the stance taken in QBism, each person's world is a physical reality with a specific quantum state; but is nonetheless different for different individuals, despite their apparently being in one and the same physical environment. To the degree they have made the same identical observations, their worlds are identically the same. But with respect to aspects of the world observed by only one of them, their worlds are different.

Clearly, a fundamental change to our current worldview is required, a scientific revolution in Kuhn's (1962) terms. There is, however, no new physics here; as stated by Fuchs et al.:

> It just requires one to recognize and abandon a strongly established way of thinking that served us reasonably well before we started to explore realms at the atomic scale. (2013, p. 3)

Rovelli considers such a change to our worldview mandated by experimental physics:

> … the notion of a universal description of the state of the world, shared by all observers, is a concept which is physically untenable, on experimental ground. (1996, p. 6)

9 Knowledge Not Belief

QBism is expressed outright as an epistemology, founded in nothing but beliefs about physical reality:

> The personal character of probability includes cases in which the agent is certain about the event: even probabilities 0 and 1 are measures of an agent's (very strongly held) belief. (Fuchs et al., 2013, p.1)

The authors specifically repudiate the idea that knowledge, or information, define the probabilities because this suggests objectivity, an: "... agent-independent factuality" (p. 9), and the beliefs of the agent are not facts, but just: "... express the willingness of the agent using them to take or place bets" (p. 9). However, on the perspective presented here, it seems knowledge must be the right word; and this also overcomes significant problems inherent in using the word belief in this context. It is the quantum mechanical frame of reference that defines the probabilities, and this is defined by a specific structure of information, the record of observations. In this context, the beliefs of agents are only evaluations and expectations, which may or may not correspond accurately to the probabilistic definition of the future given by the quantum mechanical frame of reference.

As Timpson (2008, p. 17) explains, the authors took their position in order to avoid the objectivity of quantum states, which gives rise the problems of measurement and nonlocality. However, these appear only when considering the quantum state as the definition of a specific world, a first-logical-type, outside-view perspective. As has been shown, when the quantum state is defined by the quantum mechanical frame of reference, these difficulties do not arise.

10 Psi-Ontology

QBism avoids the conceptual difficulties of quantum mechanics by associating the quantum state with a cognitive state. It can be thought of as a single-user version of the Copenhagen interpretation; and as Bohr is famous for saying, there is no reality except what is observed. QBism is presented as purely an epistemology, the knowing, not the thing itself. However, it is not necessary to abandon the quantum state as fundamental in order to reap the benefits of this perspective and thus resolve the paradoxes. The

world of the inside view has a physical definition: the superposition of quasi-classical worlds in which it is instantiated. This provides the world of QBism with an ontology, and also underscores the primary nature of the wave function since the appearance of collapse is readily explained.

Everett describes a many-perceptions framework, as proposed by Page (2011): each world is defined by the observations made, the inside view. This is why, as stated by Fuchs et al. above, physical reality differs from one agent to another. This, however, is nothing new; it is the central point of Everett's *Relative State Formulation*:

> Thus we are faced with a fundamental relativity of states, which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystem - one can only ask the state relative to a given state of the remainder of the system. (1973, p. 43)

In *Relational Quantum Mechanics*, Rovelli makes it clear that this principle applies specifically to individuals:

> ... a quantum mechanical description of a certain system (state and/or values of physical quantities) cannot be taken as an "absolute" (observer independent) description of reality, but rather as a formalization, or codification, of properties of a system relative to a given observer. (1996, p. 6)

In other words, on the inside view, the quantum state of the physical environment is relative to the individual, exactly as applies to position and velocity in relativity. This is the quantum mechanical frame of reference.

On the inside view, the quantum state is defined by the record of observations; information is primary as suggested by Wheeler (ibid). This is further supported as:

> Fuchs demonstrated that the Born rule could be rewritten almost entirely in terms of the language of probability theory, without referring to a wave function. (von Baeyer, 2013, p. 51)

The collapse dynamics is essentially an information process, operating at the emergent level of the inside view: it is the addition of each observation to the record, resulting in the change to the quantum mechanical frame of reference. Nonetheless, the wave function defines the physical reality of the inside view: the record of observations and the quantum mechanical frame of reference are equivalent. Thus the wave function defines the physical reality on both outside and inside views. It is the fundamental ontology, defining physical reality at both levels of logical type. There is nothing deeper.

11 Conclusion

As shown by Russell (1908), failing to take logical type into account produces nonsense results and paradox. Here it is proposed this is the central problem with the interpretation of quantum theory. As Tegmark describes, there are two very different views of physical reality, different kinds of frame of reference. The inside view is that of a person in the world, and the outside view is the objective physical reality, the view from nowhere. These different views are inherent in Everett's formulation, indeed axiomatic. His theory describes the difference in the way they operate, but gives no explanation of why there is this difference. As has been shown, the two kinds of frame of reference exist at different levels of logical type.

It seems utterly absurd that the physical reality should defined by the record of observations of the observer, rather than vice versa. Yet this is the conclusion of Wigner's friend: the physical reality is determinate only where observed by the individual observer. As explained by Fuchs et al.:

> The paradox vanishes with the recognition that a measurement outcome is personal to the experiencing agent. (2013)

The reason this great puzzle has haunted the science for the better part of a hundred years is because both perspectives have clear validity. It is obvious in the current paradigm that information is defined by its physical instantiation, and not vice versa. Correlations define determinacy, but this must surely be a passive reporting not a causal phenomenon. On the other hand, observation determines future outcomes. Decoherence goes part of the way to an explanation, but paradoxes remain; and these are fully resolved by taking the inside view as the determinant of the physical. This, however, seems to annihilate objectivity, anathema bordering on the irrational.

Here it is proposed that both perspectives are indeed valid and true, but at different levels of logical type. The outside view, the physical universe defined by the wave function, is the fundamental ontology. This is here taken to define the totality of all possible quasi-classical worlds. In each such world, the record of observations is defined by its physical instantiation, and has no strange influence on the physical. However, a specific inside view, the perceptual reality of a specific individual, is multiply instantiated. Taking all the quasi-classical worlds instantiating this reality to be effectively superposed, the net result is a single structure of information; and the physical world of this inside view is therefore the effectively superposed sum of all of them, defining what is here dubbed the quantum mechanical frame of reference. In this frame of reference, the physical is indeterminate except where observed.[2]

This provides the explanatory principle for the significance of the inside view which seems unbelievable on the outside view. However, it is not that the observations

2 More precisely, indeterminate except where observed, or where constrained by the inevitable implications established by observations, i.e. Bayesian in probabilistic definition.

are causal on the physical. The making of an observation simply redefines the inside view as correlated with, existing in, a different version of the physical world, defined by a different quantum mechanical frame of reference. Thus observations are causal on the inside view, while on the outside view the physical instantiation is causal on the information instantiating the observation as would be expected. The explanatory principle is that the physical world of the inside view is of different logical type to the quasi-classical worlds of the outside view, being defined by a set of such worlds.

As inherent in Everett's formulation, collapse is a purely and exclusively inside-view phenomenon. Since, in this frame of reference, the determinacy of the physical world is defined solely by the record of observations, it naturally changes when an observation is added to the record. On the making of an observation, the frame of reference changes; and thus the effective quantum state, the quantum mechanical frame of reference, changes, although nothing of the kind happens on the outside view. The new definition of the inside view is correlated with a different version of physical reality, one in which this observation, and only this observation, has been determinately made.

The measurement problem is simply resolved because the system does in fact operate the two incompatible dynamics, but at different levels of logical type. The linear dynamics is the dynamics operational within the context of a specific quantum state. It operates only on the outside view: there is no change to the inside view except when an observation is made. The collapse dynamics operates only on the inside view: there is no such phenomenon on the outside view. This is the effective change of the quantum state. Naturally, this change can only be enacted at a level of logical type higher than that at which the state of the system is defined.

Taken all together, the implications constitute a scientific revolution. On the inside view the world is as described in QBism: probabilities are defined only by what has been experienced and observed. This implies the definition of the physical world is idiosyncratic to each individual, a major conceptual and philosophical leap. The inside views are the many worlds of Everett's formulation, each defined by the quantum mechanical frame of reference. It seems clear that the assumption the inside view is nothing more than a subsidiary property of the outside view, and subject to identically the same rules, is what has led to the great paradoxes of quantum theory. As Hartle said, quoting Gell-Mann in a talk in his honour titled *Excess Baggage*:

> In my field an important new idea ... almost always includes a negative statement, that some previously accepted principle is unnecessary and can be dispensed with. Some earlier correct idea ... was accompanied by unnecessary intellectual baggage and it is now necessary to jettison that baggage. (Hartle, 1991, p. 1)

It seems clear that a universal description of the state of the world, shared by all observers is just such excess baggage, and in order to fully comprehend the mechanics we have discovered in quantum theory it is necessary to jettison that baggage. Bohm states the same principle: “In my opinion, progress in science is usually made by dropping assumptions.” (Davies, 1995, p. 199). This is perhaps never truer than here.

In Part 2, it is shown that there is an absolute requirement for an extra ontological category, in order to explain how the dynamics of the new physics come to be enacted, and make full sense of the science. This offers supporting evidence for the effective superposition of worlds containing a specific record of observations.

Appendix

As Lockwood (1989, p. 234) describes, when a measurement is made there are two stages:

> At Stage 1, there is a measurement interaction in which macroscopic states of the apparatus become systematically correlated with microscopic quantum states of the observed system. This interaction between apparatus and observed system is then followed, at Stage 2, by a second measurement interaction which results in introspectively distinguishable states of the observer's brain becoming correlated with those same macroscopic states of the apparatus.

He then explains how the appearance of collapse comes about:

> [Stage 2] involves macroscopic states becoming correlated with brain states on which consciousness somehow imposes a preferred basis. It is not, as suggested by Wigner, that our awareness precipitates a state vector reduction, at this stage. Those states of our brains to which consciousness is sensitive can, on the present view, happily evolve into superpositions that mirror superpositions in the apparatus and the observed system. These superpositions are not, however, experienced as such. There is, apparently, a preferred set of compatible brain observables, such that only eigenstates of that set constitute phenomenal perspectives. A superposition of phenomenal perspectives can exist; but it is not a phenomenal perspective in its own right. Rather, its existence is associated with the simultaneous presence of all of the phenomenal perspectives thus superposed.

As described in the main text, the phenomenal perspectives are the world holograms, the inside views, structures of information, which are operationally distinct, even within the context of a physical superposition. The question arises, why should only the eigenstates of the set of brain observables constitute phenomenal perspectives? This is addressed in Part 2.

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