The measurement problem revisited

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Abstract

It has been realized that in order to solve the measurement problem, the physical state representing the measurement result is required to be also the physical state on which the mental state of an observer supervenes. This introduces an additional restriction on the solutions to the measurement problem. In this paper, I give a new formulation of the measurement problem which lays more stress on psychophysical connection, and analyze whether Everett's theory, Bohm's theory and dynamical collapse theories can satisfy the restriction of psychophysical supervenience and thus can indeed solve the measurement problem. My analysis of the potential problems of the forms of psychophysical supervenience required by Everett's and Bohm's theories suggests that dynamical collapse theories might provide a promising solution to the measurement problem. Finally, by further analyzing how the mental state of an observer supervenes on her wave function, I also propose a possible solution to the structured tails problem of dynamical collapse theories.

1 Introduction

The measurement problem is a long-standing problem of quantum mechanics. The theory assigns a wave function to an appropriately prepared physical system and specifies that the evolution of the wave function is governed by the Schrödinger equation. However, when assuming the wave function is a complete description of the system, the linear dynamics is apparently incompatible with the appearance of definite results of measurements on the system. This leads to the measurement problem. Maudlin (1995a) gave a precise formulation of the problem in terms of the incompatibility. Correspondingly, the three approaches to avoiding the incompatibility lead to the three main solutions to the measurement problem: Everett's theory, Bohm's theory and dynamical collapse theories. It is widely thought that these theories can indeed solve the measurement problem, although each of them still has some other problems.

On the other hand, it has been realized that the measurement problem of quantum mechanics is essentially the determinate-experience problem (Barrett, 1999). In the final analysis, the problem is to explain how the linear dynamics can be compatible with the existence of definite experiences of conscious observers. This requires that the physical state representing the measurement result should be also the physical state on which the mental state of an observer supervenes,[1] thus introducing an additional important restriction on the solutions to the problem. However, this aspect of the measurement problem is ignored in Maudlin's (1995a) formulation. Moreover, although there have been some discussions on psychophysical supervenience in a particular solution to the measurement problem (e.g. Brown, 1996; Barrett, 1999; Brown and Wallace, 2005; Lewis, 2007), a systematic analysis of psychophysical supervenience in all main solutions to the measurement problem seems still missing in the literature. In this paper, I will first give a new formulation of the measurement problem which gives prominence to the psychophysical connection, and then analyze whether each of the three main solutions to the measurement problem can satisfy the restriction of psychophysical supervenience, and thus can indeed solve the measurement problem.

This paper is organized as follows. In Section 2, I first introduce Maudlin's conventional formulation of the measurement problem, and then suggest a new formulation of the problem which lays more stress on the aspect of psychophysical supervenience. It is pointed out that the three main solutions to the measurement problem correspond to three different forms of psychophysical supervenience. In Section 3, Everett's theory is analyzed. The theory requires that the mental state of an observer cannot always supervene on her whole wave function, and especially, for a post-measurement wave function it supervenes on certain branches of the wave function. It is argued that this form of partial psychophysical supervenience seems problematic, and resorting to decoherence may lead to a further problem. In Section 4, the problems of Bohm's theory relating to psychophysical supervenience are analyzed. It is argued that the two suggested forms of psychophysical supervenience meet difficulties. In particular, the well-accepted form of psychophysical supervenience (i.e. the form that the mental state supervenes only on the positions of Bohmian particles) may also lead to an inconsistency problem besides the problem of allowing superluminal signaling. In Section 5, dynamical collapse theories are analyzed. It is pointed out that

[1] In this paper I will not consider the possibility that there is no physical state representing the measurement result on which the mental state of an observer may supervene.

although these theories are favored by the above analysis of psychophysical supervenience, they are also plagued by a few serious problems such as the structured tails problem. A possible solution to this problem is proposed based on a further analysis of how the mental state of an observer supervenes on her wave function. Conclusions are given in the last section.

2 A new formulation of the measurement problem

According to Maudlin's (1995a) formulation, the measurement problem originates from the incompatibility of the following three claims:

(C1). the wave function of a physical system is a complete description of the system;

(C2). the wave function always evolves in accord with a linear dynamical equation, e.g. the Schrödinger equation;

(C3). each measurement has a definite result (which is one of the possible measurement results whose probability distribution satisfies the Born rule).

The proof of the inconsistency of these three claims is familiar. Suppose a measuring device M measures the x-spin of a spin one-half system S that is in a superposition of two different x-spins $1/\sqrt{2}(|up\rangle_S + |down\rangle_S)$. If (C2) is correct, then the state of the composite system after the measurement must evolve into the superposition of M recording x-spin up and S being x-spin up and M recording x-spin down and S being x-spin down:

$$1/\sqrt{2}(|up\rangle_S |up\rangle_M + |down\rangle_S |down\rangle_M). \tag{1}$$

The question is what kind of state of the measuring device this represents. If (C1) is also correct, then this superposition must specify every physical fact about the measuring device. But by symmetry of the two terms in the superposition, this superposed state cannot describe a measuring device recording either x-spin up or x-spin down. Thus if (C1) and (C2) are correct, (C3) must be wrong.

It can be seen that there are in general three approaches to solving the measurement problem thus formulated. The first approach is to deny the claim (C1), and add some additional variables and corresponding dynamics to explain the appearance of definite measurement results. A well-known example is Bohm's theory (Bohm, 1952). The second approach is to deny the claim (C2), and revise the Schrödinger equation by adding some nonlinear and stochastic evolution terms to explain the appearance of definite measurement results. Such theories are called dynamical collapse theories (Ghirardi, 2011). The third approach is to deny the claim (C3), and assume the existence of many equally real worlds to accommodate all possible results of measurements (Everett, 1957; DeWitt and Graham, 1973). In this way, it may also explain the appearance of definite measurement results in each world including our own world. This approach is called Everett's interpretation of quantum mechanics or Everett's theory.

It has been realized that the measurement problem in fact has two levels: the physical level and the mental level, and it is essentially the determinate-experience problem (Barrett, 1999). The problem is not only to explain how the linear dynamics can be compatible with the existence of definite measurement results obtained by physical devices, but also, and more importantly, to explain how the linear dynamics can be compatible with the existence of definite experiences of conscious observers. However, the mental aspect of the measurement problem is ignored in Maudlin's (1995a) formulation. Here I will suggest a new formulation of the measurement problem which lays more stress on the psychophysical connection. In this formulation, the measurement problem originates from the incompatibility of the following two claims:

(P1). the mental state of an observer supervenes on her wave function;

(P2). the wave function always evolves in accord with a linear dynamical equation, e.g. the Schrödinger equation.

The proof of the inconsistency of these two claims is similar to the above proof. Suppose an observer M measures the x-spin of a spin one-half system S that is in a superposition of two different x-spins, $1/\sqrt{2}(|up\rangle_S + |down\rangle_S)$. If (P2) is correct, then the physical state of the composite system after the measurement will evolve into the superposition of M recording x-spin up and S being x-spin up and M recording x-spin down and S being x-spin down:

$$1/\sqrt{2}(|up\rangle_S |up\rangle_M + |down\rangle_S |down\rangle_M). \tag{2}$$

If (P1) is also correct, then the mental state of the observer M will supervene on this superposed wave function. Since the mental states corresponding to the physical states $|up\rangle_M$ and $|down\rangle_M$ differ in their mental content, the observer M being in the superposition (2) will have a conscious experience different from the experience of M being in each branch of the superposition by the symmetry of the two branches. In other words, the record that M is consciously aware of is neither x-spin up nor x-spin down when she is physically in the superposition (2). This is inconsistent with experimental observations. Therefore, (P1) and (P2) are incompatible.

By this new formulation of the measurement problem, we can look at the three major solutions of the problem from a new angle. First of all, the solution to the measurement problem must deny either the claim (P1) or the claim (P2). If (P1) is correct (as usually thought), then (P2) must be wrong. In other words, if the mental state of an observer supervenes on her wave function, then the Schrödinger equation must be revised and the solution to the measurement problem will be along the direction of dynamical collapse theories. On the other hand, if (P2) is correct, then (P1) must be wrong. This means that if the wave function always evolves in accord with the Schrödinger equation, then the mental state of an observer cannot supervene on her wave function. There are two other forms of psychophysical supervenience. One is that an observer may have many mental states and these mental states supervene on certain branches of her wave function,[2] and the other is that the mental state of an observer supervenes on other additional variables. The first form corresponds to Everett's theory, and the second form corresponds to Bohm's theory.

To sum up, the three major solutions to the measurement problem correspond to three different forms of psychophysical supervenience. In fact, there are only three types of physical states on which the mental state of an observer may supervene, which are (1) the wave function, (2) certain branches of the wave function, and (3) other additional variables. The question is: Exactly what physical state does the mental state of an observer supervene on? It can be expected that an analysis of this question will help solve the measurement problem.

3 Everett's theory

I will first analyze Everett's theory. The theory claims that for the above post-measurement state (2) there are two observers, and each of them is consciously aware of a definite record, either x-spin up or x-spin down.[3]

There are in general two ways of understanding the notion of multiplicity in Everett's theory. One is the strong form which claims that there are two *physical* observers (in material content) after the quantum measurement (e.g. DeWitt and Graham, 1973). The resulting theory is called many-worlds theory. In this theory, a physical observer always has a unique mental state, and the mental state also supervenes on the whole physical state of the observer, although which may be only a branch of the superposed wave function. Thus this theory is consistent with the common assumption of psychophysical supervenience, according to which the mental state of a physical observer supervenes on her whole physical state. As is well known, however, this theory has serious problems such as violation of mass-energy conservation and inconsistency with the dynamical equations (Albert and Loewer, 1988). The problem of inconsistency can also be seen as follows.

[2]If an observer always has a unqiue mental state and the mental state supervenes only on a certain branch of her wave function, then the psychophysical supervenience will be obviously violated. This is the case of the single-mind theory (Albert and Loewer, 1988; Barrett, 1999). Although I will not discuss this theory below, some of my analyses also apply to this theory.

[3]Note that in Wallace's (2012) latest formulation of Everett's theory the number of the emergent observers after the measurement is not definite due to the imperfectness of decoherence. I will discuss this point later.

The existence of many worlds is only relative to decoherent observers, not relative to non-decoherent observers, who can measure the whole superposition corresponding to the many worlds (e.g. by protective measurements) and confirm that there is no increase in the total mass-energy and number of particles.

The other way of understanding the notion of multiplicity is the weak form which claims that there is one *physical* observer (in material content), but there are two *mental* observers or two mental states of the same physical observer, after the quantum measurement (e.g. Zeh, 1981). Wallace's (2012) latest formulation of Everett's theory is arguably this view in nature (see also Kent, 2010).[4] In order to derive the multiplicity prediction of the weak form of Everett's theory, a physical observer cannot always have a unique mental state, and when she has more than one mental states, each mental state does not supervene on her whole physical state either. For example, when the observer is in one of the two physical states $|up\rangle_M$ and $|down\rangle_M$, she has a unique mental state and the mental state also supervenes on her whole physical state. While when she is in a superposition of these two physical states such as (2), she has two mental states but each mental state does not supervene on her whole physical state; rather, each mental state supervenes only on a part of the whole physical state, such as one of the two terms in the superposition (2). Therefore, different from the strong form of Everett's theory, the weak form of Everett's theory obviously violates the common assumption of psychophysical supervenience.[5]

One may argue that the psychophysical supervenience is not really violated here, since the sum of all mental states of a physical observer do supervene on her whole physical state. However, this argument is problematic. First of all, since these mental states may be incompatiable with each other, the sum of these mental states is arguably not a valid mental state. For instance, the combination of the mental state of seeing a cat and the mental state of not seeing a cat seems meaningless. Thus, strictly speaking, this form of supervenience is not really a form of psychophysical supervenience. Next, as Barrett (1999, p.196) has argued, if one wants psychophysical supervenience, then one presumably wants the mental state

[4]In Wallace's formulation, it is claimed that there are also two emergent physical observers after the quantum measurement, but their existence is only in the sense of branch structure (i.e. the structure of certain parts of the whole physical state), not in the sense of material content. Therefore, strictly speaking, there is only one physical observer with her whole physical state in Wallace's formulation. If such a theory is also regarded as a many-worlds theory, then these worlds should be not physical worlds but mental worlds.

[5]The common assumption of psychophysical supervenience is arguably reasonbale. A whole physical state is independent, while any two parts of the state are not independent; once one part is selected, the other part will be also fixed. Since a mental state is usually assumed to be autonomous, it is arguably that a mental state supervenes on a whole physical state, not on any part of the state.

that determines one's experience and the only mental state to which one has epistemic access to supervene on one's physical state. But in the weak form of Everett's theory, when a physical observer has many mental states, each mental observer can only have epistemic access to her own mental state, and thus the sum of all these mental states is certainly not a mental state that satisfies this requirement of psychophysical supervenience.

Certainly, one may also insist that the common assumption of psychophysical supervenience is not valid in general in the quantum domain. But even though this is true, one still needs to explain why, in particular, why this assumption applies to the physical states $|up\rangle_M$ and $|down\rangle_M$, but not to any superposition of them. This is similar to the preferred basis problem. It seems that the only difference one can think is that being in the superposition the physical observer has no definite mental state which contains a definite conscious experience about the measurement result, while being in each branch of the superposition, $|up\rangle_M$ or $|down\rangle_M$, she has a definite mental state which contains a definite conscious experience about the measurement result. However, it has been argued that the common assumption of psychophysical supervenience can also be applied to general quantum superpositions, and moreover, under this assumption a physical observer being in a post-measurement superposition such as (2) also has a definite mental state which contains a definite conscious experience about the measurement result (Gao, 2016). Note that these analyses also apply to the many-minds theory, which is similar to the weak form of Everett's theory in many aspects (Albert and Loewer, 1988; Barrett, 1999).

Finally, I will give a brief comment on the relationship between Everett's theory and decoherence. It is usually thought that the appearance of many observers after a quantum measurement is caused by decoherence. However, even if this claim is true for the strong form of Everett's theory, it seems that it cannot be true for the weak form of the theory. The reason is that the generation of a superposed state of a physical observer (e.g. a superposition of two physical states $|up\rangle_M$ and $|down\rangle_M$), as well as the psychophysical supervenience, have nothing to do with decoherence. Indeed, the weak form of Everett's theory is more like a many-minds theory than like a many-worlds theory.

In addition, resorting to decoherence seems to cause a further difficulty for the application of the doctrine of psychophysical supervenience. Since decoherence is never perfect, there will be no definite parts of the whole physical state on which the mental states can supervene. This objection also applies to Wallace's (2012) formulation of Everett's theory, which is arguably a weak form of the theory. Note again that in the weak form of Everett's theory the observer still has a whole physical state after a quantum measurement. In my opinion, it is the failure to clearly distinguish between the weak form and the strong form of Everett's theory in the literature that causes much confusion in understanding Everett's theory (see also Kent, 2010).

4 Bohm's theory

Let us now turn to Bohm's theory. It has been realized that an analysis of psychophysical supervenience in Bohm's theory is also relevant and necessary (Brown, 1996). In this theory, there are two suggested forms of psychophysical supervenience. The first one is that the mental state supervenes on the branch of the wave function occupied by the Bohmian particles. The second one is that the mental state supervenes only on the (relative) positions of Bohmian particles.

The first form of psychophysical supervenience has been the standard view until recently, according to which the mental state of an observer being in a post-measurement superposition like (2) supervenes only on the branch of the superposition occupied by the Bohmian particles. Indeed, Bohm initially assumed this form of psychophysical supervenience. He said: "the packet entered by the apparatus [hidden] variable... determines the actual result of the measurement, which the observer will obtain when she looks at the apparatus." (Bohm, 1952, p.182). In this case, the role of the Bohmian particles is merely to select the branch from amongst the other non-overlapping branches of the superposition. Brown and Wallace (2005) called this assumption Bohm's result assumption, and they have presented some arguments against it (see also Stone, 1994; Brown, 1996; Zeh, 1999; Lewis, 2007).

According to Brown and Wallace (2005), in the general case each of the non-overlapping branches in the final joint-system configuration space wavefunction has the same credentials for representing a definite measurement result as the single branch does in the predictable case (i.e. the case in which the measured system is in an eigenstate of the measured observable). The fact that only one of them carries the Bohmian particles does nothing to remove these credentials from the others, and adding the particles to the picture does not interfere destructively with the empty branches either. In my view, the main problem with this form of psychophysical supervenience is that the empty branches and the occupied branch have the same qualification to be supervened by the mental state. Moreover, although it is imaginable that the Bohmian particles may have influences on the occupied branch, e.g. disabling it from being supervened by the mental state, it is hardly imaginable that the Bohmian particles have influences on all other empty branches, e.g. disabling them from being supervened by the mental state.

In view of the first form of psychophysical supervenience being problematic, most Bohmians today seem to support the second form of psychophysical supervenience (e.g. Holland, 1993, p.334), although they sometimes do not state it explicitly (e.g. Maudlin, 1995b). At first sight, if assuming this form of psychophysical supervenience, namely assuming the mental state supervenes only on the (relative) positions of Bohmian particles, then it seems that the above problems can be avoided. However, it has been argued that this form of psychophysical supervenience is inconsistent with the popular functionalist approach to consciousness (Brown and Wallace, 2005; see also Bedard, 1999). The argument can be summarized as follows. If the functionalist assumption is correct, for consciousness to supervene on the Bohmian particles but not the wavepackets, the Bohmian particles must have some functional property that the wavepackets do not share. But the functional behaviour of the Bohmian particles is arguably identical to that of the wavepacket in which they reside. Moreover, this form of psychophysical supervenience also leads to another problem of allowing superluminal signaling (Brown and Wallace, 2005; Lewis, 2007). If the mental state supervenes on the positions of Bohmian particles, then an observer can in principle know the configuration of the Bohmian particles in her brain with a greater level of accuracy than that defined by the wave function. This will allow superluminal signaling and lead to a violation of the no-signalling theorem (Valentini, 1992).[6]

A more serious problem with the second form of psychophysical supervenience, in my view, is that it seems inconsistent with the Born rule.[7] Consider again an observer being in the post-measurement superposition (2). According to the Born rule, the modulus squared of the amplitude of each branch of this superposition represents the probability of obtaining the measurement result corresponding to the branch. For example, the modulus squared of the amplitude of the branch $|up\rangle_M$ represents the probability of obtaining the x-spin up result. This means that the Born rule requires that the quantities that representing the measurement results should be correlated with these branches of the superposition.[8] Then, in order that the measurement result is represented by the relative positions of the Bohmian particles as required by the second form of psychophysical supervenience, there must exist a correspondence between different branches of the superposition and different relative positions of the Bohmian particles, and in particular, the relative positions of the Bohmian particles corresponding to different branches of the superposition must be different.

However, Bohm's theory does not give such a corresponding relation-

[6]In my view, this problem is not as serious as usually thought, since the existence of such superluminal signaling is not inconsistent with experience, and superluminal signaling may also exist in other theories such as dynamical collapse theories (Gao, 2004, 2014d).

[7]This inconsistency problem originates only from the assumption that the measurement result is represented by the positions of the Bohmian particles, and it is independent of the psychophysical connection.

[8]Note that this requirement is independent of whether the wave function is ontic or not.

ship, and thus it is at least incomplete when assuming the second form of psychophysical supervenience. Moreover, it can be argued that the corresponding relationship does not exist. The probability of the Bohmian particles appearing at a location in configuration space is equal to the modulus squared of the amplitude of the wave function at the location. It is permitted by the linear dynamics that one branch of the post-measurement superposition (2) is a spatial translation of the other branch, e.g. the spatial part of $|down\rangle_M$ is $\psi(x_1, x_2, t)$, and the spatial part of $|up\rangle_M$ is $\psi(x_1 + a, x_2 + a, t)$. Then if a relative configuration of the Bohmian particles appears in the region of one branch in configuration space, it may also appear in the region of the other branch in configuration space. Moreover, the probability densities that the configuration appears in both regions are the same. This means that a relative configuration of the Bohmian particles can correspond to either branch of the superposition, and there does not exist a corresponding relationship between different branches of the superposition and different relative configurations of the Bohmian particles. As a result, if the measurement result is represented by the relative positions of the Bohmian particles as required by the second form of psychophysical supervenience, then no matter which branch of the superposition the Bohmian particles reside in after the measurement, the measurement result will be the same. This is obviously inconsistent with the Born rule. Note that this inconsistency problem not only exists for the above special type of superpositions, but also exists for most post-measurement superpositions, for each of which the probability densities that a relative configuration of the Bohmian particles appears in the regions of two of its non-overlapping branches are both larger than zero.

Finally, I note that the above analysis of psychophysical supervenience also raises a doubt about the whole strategy of Bohm's theory to solve the measurement problem. Why add hidden variables such as positions of Bohmian particles to quantum mechanics? It has been thought that adding these variables which have definite values at every instant is enough to ensure the definiteness of measurement results and further solve the measurement problem. However, if the mental state cannot supervene on these additional variables, then even though these variables have definite values at every instant, they are unable to account for our definite experience and thus do not help solve the measurement problem.

5 Dynamical collapse theories

I have argued that one will meet some difficulties if assuming the mental state of an observer supervenes either on certain branches of her wave function or on other additional variables, and thus it seems that Everett's and Bohm's theories are not promising solutions to the measurement problem. This also suggests that the mental state of an observer supervenes directly on her wave function, and dynamical collapse theories may be in the right direction to solve the measurement problem. In some sense, these arguments can be seen as a further development of von Neumann's (1955) argument for the collapse postulate based on the doctrine of psychophysical parallelism.

However, it has been known that dynamical collapse theories are still plagued by a few serious problems such as the tails problem (Albert and Loewer, 1996). In particular, the structured tails problem has not been solved in a satisfactory way (see McQueen, 2015 and references therein). The problem is essentially that dynamical collapse theories such as the GRW theory predicts that the post-measurement state is still a superposition of different outcome branches with similar structure (although the modulus squared of the coefficient of one branch is close to one), and they need to explain why high modulus-squared values are macro-existence determiners (McQueen, 2015). In my view, the key to solving the structured tails problem is not to analyze the connection between high modulus-squared values and macro-existence, but to analyze the connection between these values and our experience of macro-existence, which requires us to further analyze how the mental state of an observer supervenes on her wave function.

Admittedly this is an unsolved, difficult issue, but I will give a few speculations here. I conjecture that the mental content of an observer being in a post-measurement superposition like (2) is composed of the mental content corresponding to every branch of the superposition, and in particular, the modulus squared of the amplitude of each branch determines the vividness of the mental content corresponding to the branch (Gao, 2016). Under this assumption, when the modulus squared of the amplitude of a branch is close to zero, the mental content corresponding to the branch will be the least vivid. It is conceivable that below a certain threshold of vividness an ordinary observer or even an ideal observer will not be consciously aware of the corresponding mental content. Then even though in dynamical collapse theories the post-measurement state of an observer is still a superposition of different outcome branches with similar structure, the observer can only be consciously aware of the mental content corresponding to the branch with very high amplitude, and the mental content corresponding to the branches with very low amplitude will not appear in the whole mental content of the observer. This may solve the structured tails problem of dynamical collapse theories.

6 Conclusions

It has been realized that the measurement problem, in the final analysis, is to explain how the linear quantum dynamics can be compatible with the existence of definite experiences of conscious observers. This requires that the physical state representing the measurement result should be also the physical state on which the mental state of an observer supervenes, thus introducing an important restriction on the solutions to the measurement problem. However, the mental aspect of the measurement problem has been ignored in the conventional formulation of the problem, and a systematic analysis of psychophysical supervenience in the solutions to the problem is also missing in the literature. In this paper, I give a new formulation of the measurement problem which lays more stress on the psychophysical connection, and analyze whether the three main solutions to the problem, namely Everett's theory, Bohm's theory and dynamical collapse theories, can satisfy the restriction of psychophysical supervenience and thus can indeed solve the problem. The analysis suggests that dynamical collapse theories may be in the right direction to solve the measurement problem. Finally, I also propose a possible solution to the structured tails problem of dynamical collapse theories by a further analysis of psychophysical supervenience.

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