The many-worlds view of quantum mechanics

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Abstract

A particular version of the many-worlds interpretation is presented. I argue that the only ontology of quantum mechanics is the universal wavefunction following unitary deterministic evolution. The other part of the theory are postulates connecting experiences of agents in multiple parallel worlds with branches of this wavefunction.

A few decades ago I spent a day of discussions with David Bohm and I remember telling him that I liked his theory, Bohm (1952), because it is a candidate for an ontological theory which explains everything. David's reply was that this is nonsense: humans are limited, and we will never find such a theory, only a better and better approximation of it. Many interpretations agree with Bohm's approach asserting that quantum physics is only capable of telling us how to predict the outcomes of measurements we perform, not what Nature is. My colleagues often start teaching students quantum mechanics saying that they only can explain how to use it, not what it means. Working on foundations of quantum mechanics starting with my Ph.D. studies with Yakir Aharonov, I feel that we can be more optimistic.

I want to believe that today we understand Nature. I do not try to understand why our world happened to be this particular one and not another. I only try to understand how our world works. Beyond predicting the outcomes of measurements, I want to explain the process of measurements. The task is to identify in all that we know sets of similar situations which can be considered as preparations of measurements and to find a theory that explains the common patterns of behavior in these situations, the results of measurements. At the end of the 18th century there was a feeling that science reached a satisfactory solution for this task. However, this famous quote of Lord Kelvin (1901) shows that this feeling was very wrong:

> The beauty and clearness of the dynamical theory, which asserts that heat and light are modes of motion, is at present obscured by two clouds.

Physics was completely changed by the two clouds that Kelvin was referring to - the theory of relativity and quantum mechanics. Today we have a much better reason to believe that we understand Nature: experimental data and predictions of our current theory agree with unprecedented precision. We do not have a satisfactory quantum explanation of gravity, which the physics community expects, but this fact is not relevant to explaining experiments that we perform.

In spite of the extraordinary success of science in explaining the results of experiments, the view that today we understand Nature is not popular. One sociological reason is our memory that we were very wrong in 1900 asserting that we understand Nature, when we had no quantum and relativistic theories. Still, maybe the main reason is that, paraphrasing Lord Kelvin, the beauty and clearness of the dynamical theory is at present obscured by one big cloud: the measurement problem.

Equations of quantum mechanics describing quantum measurements have terms corresponding to all possible outcomes, but in the laboratory we always observe only one of them. How do we resolve this difficulty? Physicists were looking for alternative equations that yield one outcome, like in all situations described by classical physics from the time of Lord Kelvin, but without success. Another approach is to accept the equations of evolution of quantum states but add equations that remove all the terms appearing in measurement procedures except the one that corresponds to the observed result. Von Neumann postulated that all other terms disappear without providing any mechanism in mathematical terms. To justify this ad hoc and vaguely defined postulate, he showed that we would not be able to see a difference between a wide range of mechanisms erasing the other terms. Among the physical proposals for such a mechanism Pearle (1976); Ghirardi, Rimini, & Weber (1986); Diósi (1987); Penrose (1996), most also have an *ad hoc* character. Instead of changing the evolution of quantum states, David Bohm suggested adding the ontology of particle positions, Bohm (1952), which singles out one result for each quantum measurement.

I understand the motivation for having, in theory, only the measurement results we observe in a laboratory, but since all current proposals achieving this are radically different from all other aspects of physics that are tremendously successful in explaining all that we observe, I cannot accept these proposals. The main issue is that they all introduce action at a distance, see Vaidman (2024b). I prefer to keep physics clear and elegant without non-local actions. This leads me to abandon the von Neumann process of type I, to reject modifications of standard quantum mechanical equations, and to avoid adding new ontology like Bohmian positions of particles. There is a price: accepting a multiplicity of worlds corresponding to all measurement outcomes.

Let me present here an example to demonstrate the many-worlds interpretation (MWI) and action at a distance of a single-world interpretation. The principle of superposition is well established for microscopic objects like atoms, see Fig. 1a. If there are two stable states of an atom, the ground state $|g\rangle$ and a particular excited state $|e\rangle$, then the atom can be in a superposition state, e.g.

$$\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle). \tag{1}$$

The MWI states that the superposition principle is universally valid, not just for microscopic systems, but for cats, people, measuring devices, etc. So, if we have the state of a macroscopic pointer measuring the ground state of the atom, $|G\rangle_{MD}$ and we have the state of a macroscopic pointer measuring the excited state of the atom, $|E\rangle_{MD}$ then the superposition state

$$\frac{1}{\sqrt{2}}(|E\rangle_{MD} + |G\rangle_{MD}). \tag{2}$$

exists too, see Fig. 1b.

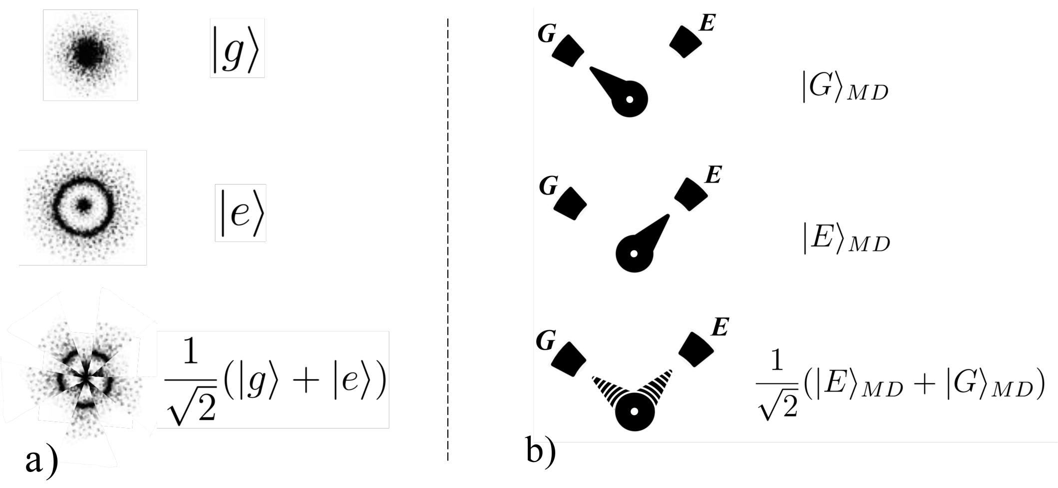

Figure 1: **Superposition principle.** a) If an atom can be in state $|g\rangle$ and it can be in state $|e\rangle$ then it can be in state $\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$. b) If a pointer of the measuring device can be in state $|G\rangle_{MD}$ and it can be in state $|E\rangle_{MD}$ then it can be in state $\frac{1}{\sqrt{2}}(|G\rangle_{MD} + |E\rangle_{MD})$. For macroscopic measuring devices the principle holds in the the framework of MWI, but it *does not* hold in the frameworks of single-world interpretations.

The 2022 Nobel Prize in Physics for the experimental demonstrations of nonlocal features of quantum mechanics was apparently triggered by "loophole-free" Bell-type experiments with, arguably, the most convincing results in Munich, see Rosenfeld, Burchardt, Garthoff, Redeker, Ortegel, Rau, & Weinfurter (2017). These experiments show that quantum superposition holds for two separated in space (400 meters in the Munich experiment) atoms A and B. We can have a state with an atom A in an excited state and an atom B in a ground state, $|e\rangle_A|g\rangle_B$. We can also have an excited atom B and a ground state atom A, $|g\rangle_A|e\rangle_B$. The experiments showed that the entangled state of the atoms, the superposition

$$\frac{1}{\sqrt{2}}(|e\rangle_A|g\rangle_B + |g\rangle_A|e\rangle_B).,\tag{3}$$

exists too, see Fig. 2.

In the framework of MWI, the measurement of the state of atom A of the entangled pair (3) is described in the following way:

$$\frac{1}{\sqrt{2}}|R\rangle_{MD}(|e\rangle_A|g\rangle_B + |g\rangle_A|e\rangle_B) \to \frac{1}{\sqrt{2}}(|E\rangle_{MD}|e\rangle_A|g\rangle_B + |G\rangle_{MD}|g\rangle_A|e\rangle_B).\tag{4}$$

In view of the experimental results of loophole-free Bell experiments, single-world interpretations cannot reject the existence of the state (3) of entangled atoms, but since there is no technology that can test for the interference of macroscopic bodies, these interpretations implicitly postulate that superpositions of macroscopically different macroscopic states like (2) do not exist. For single-world interpretation, this postulate is also a necessity. Without this postulate, two different readings of the measuring device coexist. This is the co-existence of two histories, the superposition of two worlds. This is the MWI.

The measurement process of an atom is not instantaneous, but it is a local operation at site A and, therefore, the duration of the measurement does not depend on the distance between the sites A and B. In the loophole-free Bell-type experiments, the duration of

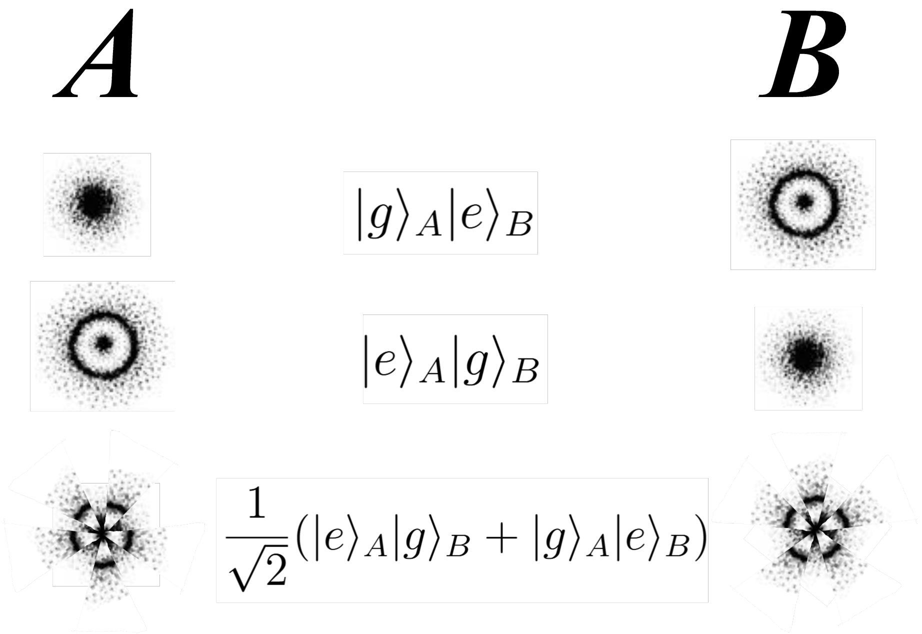

Figure 2: **Separated atoms in an entangled state.** The superposition principle holds for separated atoms. We have two different states in which one atom is in the ground state and another in excited state. The superposition of these states exists too.

the measurement of the state of the atom was shorter than the time required for light to go from A to B. If something in site B becomes different between the situation described by (3) and the right-hand side of (4), the measurement in A would cause a superluminal change in B, violating the special theory of relativity. For MWI, however, this is not the case; see Figs. 3a and 3b. The atom in B has the same local description in two cases; it is a mixed state described density matrix

$$\rho_B = \frac{1}{2}\left(|g\rangle\langle g| + |e\rangle\langle e|\right). \tag{5}$$

In single-world interpretations the process (4) cannot happen, as it leads to a superposition of macroscopically different state of a macroscopic pointer, or, it immediately must be followed by the collapse to a quantum state corresponding to one result, see Figs. 3c and 3d. Thus, the time evolution of the atoms and the measuring device measuring atom A is, instead,

$$\frac{1}{\sqrt{2}}|R\rangle_{MD}(|e\rangle_A|g\rangle_B + |g\rangle_A|e\rangle_B) \rightarrow \Big\{|E\rangle_{MD}|e\rangle_A|g\rangle_B \quad \text{or} \quad |G\rangle_{MD}|g\rangle_A|e\rangle_B\Big\}. \tag{6}$$

This is action at a distance! If we do not make measurements of the atom in A, we remain with the entangled state (3) and the local description of the atom B is given by a mixed state (5). If we perform a measurement in A, the atom in B immediately changes from the mixed state (5) to the pure state $|e\rangle_B$ or $|g\rangle_B$.

A local observer will not be able to observe the change. For her, it was (in d'Espagnat (2018) language) an " improper mixture" (5) before the measurement and a "proper mixture" $\{|g\rangle\langle g| \ \text{ or } \ |e\rangle\langle e|\}$ after the measurement. The "proper" mixture is a subjective description of an observer who is ignorant of the complete description of the universe. The

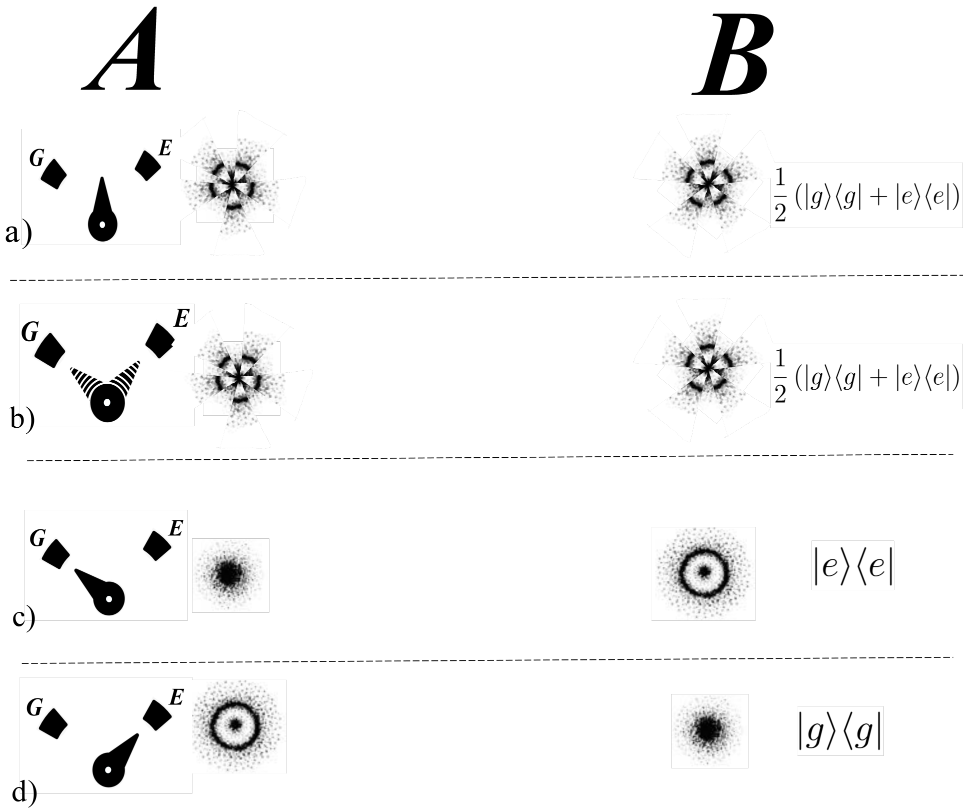

Figure 3: **Action at a distance.** a) Description of entangled atoms before avmeasurement in A. b) Description of entangled atoms after a measurement in A in the framework of MWI. Local description in B remains the same as it was in (a). c-d) Description of entangled atoms after a measurement in A in the framework of single-world interpretations. There are two possible different outcomes, but in both cases the local description in B is different from what it was in (a).

local indistinguishability between proper and improper mixtures ensures the impossibility of superluminal signaling despite the presence of action at a distance. Proper and improper mixtures are objectively different. Everyone will be ready to place a bet on an atom in an improper mixture because everyone knows that no one has a better knowledge about the outcome than a random guess. This is not true for an atom in a proper mixture. Since there is a matter of fact about the state of the atom: it is either in the ground state or in the excited state, someone might know, so there is no reason to agree on the bet, if it is suggested to you.

Abandoning collapse leads to many worlds. However, there are many versions of MWI. In my version, I abandon not only the collapse of the universal wavefunction but also refuse to add *anything else* to my physical theory: no ontological worlds named "universes", DeWitt (1971), no ontological minds of "many-minds view" Albert & Loewer (1988), no ontology of agents as four-dimensional "worms" Wilhelm (2023). The physical (mathematical) part of my version of MWI postulates even less than the "bare theory" of quantum mechanics Albert (1992), because I do not postulate the eigenvalue-eigenstate link. Instead, I add a non-mathematical part to the theory that connects the ontology with the experience of sentient beings. In terms of physics, I postulate as given the three-dimensional space (3D) instead of trying to derive it as Carroll & Singh (2019).

My explanation has two very different parts.
i) The ontology, stuff that exists, including laws constraining possible states of stuff and dynamical laws of time evolution of stuff.
ii) The prescription of correspondence of the state of stuff with our experiences which we inquire through our sensory organs, sometimes equipped with instruments like telescopes, microscopes, sonars, etc.

To define part (i), I start with 3D. For Newtonian mechanics, stuff is point-like particles placed in 3D. There are no constraints for the configuration of particles and their velocities (apart from not putting particles on top of each other because of the singularity of local interactions). Newtonian mechanics with Newtonian gravity, which features action at a distance, has to be modified by adding fields to mediate the interactions to avoid action at a distance. The stuff has two forms: particles and fields. However, fields and matter could not be arbitrarily distributed in space. The first pair of Maxwell's equations (the equations without time derivative) are strong constraints on possible configurations of charges and fields. Empirical evidence shows that classical physics is incorrect, so the equations must be modified again. We have to be in the framework of quantum mechanics. Particles are now represented by wavefunctions. Relativistic corrections make us move to fields, wave functionals, (maybe strings?!) so even part (i), the nature of stuff, has to be modified. However, I do not foresee revolutionary changes in the solution of the measurement problem when we move to the next-level theories that are necessary for analyzing physics at a higher energy scale.

Apart from putting constraints on the configuration of stuff, part (i) also has dynamical laws that specify the evolution of stuff with time. The basic equation is the Shrödinger equation, but of course the exact equation will be its relativistic generalization. I consider the dynamical laws of a theory to be the most important part. The constraints tell us the options for the universe given our theory. But there is one actual universe, and the hypothetical question of what it could have been is of some philosophical interest, but it does not add much to the main question I want to understand: how the universe works. In our current memories, there is a large set of situations that can be considered as preparations of measurements together with their results. The regularities of these records are what I want to explain: the connections between preparations and results. These connections are given by dynamical laws. Note, that the constraint laws are for the universe, but they provide constraints in all worlds. The constraint laws shed light on why we have in our memories a particular set of preparations and not the other, which I find a less urgent and important question.

The formalism of quantum mechanics, even without many worlds, does not provide a simple, transparent picture corresponding to our experience. Maudlin (2010) strongly opposes the idea that the quantum state defined in the configuration space can describe the reality that we experience in 3D. In order to avoid changing the standard paradigm of a physical theory that does not have part (ii), many physicists try to modify the quantum formalism in such a way that it will lead to a familiar picture of the reality we see. The influential work of Bell (1976) led many to look for local beables that can provide a familiar picture of reality in 3D. Today, it has the name of primitive ontology, Allori, Goldstein, Tumulka, & Zanghì (2014), with Bohmian positions of particles as the main example, supported by the fact that the trajectories of the Bohmian particles look very much like the trajectories of classical particles.

However, the formalism of Bohmian mechanics without the postulate of part (ii) has an ambiguity. The pilot wave of Bohmian mechanics is the wavefunction of the MWI, which arguably can also provide an explanation of our experience(s). So, there is no unique way to connect the formalism to our experience. In fact, in Bohmian mechanics, there is also a third way that connects the experience with the effective "collapsed" wavefunction of the observer defined by the location of Bohmian positions of systems entangled with the observer, see Vaidman (2024a).

The Bohmian effective collapsed wave function is very similar to the original GRW-Pearle wavefunction. Both differ very little from the von Neumann collapsed wavefunction, the wavefunction explicitly or implicitly considered in textbooks on quantum mechanics. For half a century, roughly until the experiment by Aspect, Grangier, & Roger (1981), physicists accepted this wavefunction as the ontology which explains well the observed reality. Sometimes, the wavefunction was considered as part of reality together with the classical physics required to describe measuring devices, see Landau & Lifshitz (2013). The measurement problem was that dynamical equations that describe a measurement process, such as (4) led to a detector that simultaneously shows several different outcomes, such as $|G\rangle_{MD}$ and $|E\rangle_{MD}$. Only the addition of collapse, the von Neumann process I, led to a wavefuntion corresponding to a single outcome $|G\rangle_{MD}$ or $|E\rangle_{MD}$. The eigenvalue - eigenstate link was essentially the postulate of correspondence between ontology and experience. The classical physics connection to experience was accepted without stating it, so the eigenvalue - eigenstate link connected the collapsed wavefunction and experience.

Even if the effectively collapsed Bohmian wavefunction, the GRW and gravitational collapse wavefunctions, and the von Neumann collapsed wavefunction are not exactly identical, they are the same for all practical purposes (FAPP) Bell (1990). In part (ii) I want to use this FAPP concept of collapsed wavefunction to connect ontology and experience. If we try to use this concept to define the physical process of collapse, its vagueness is unacceptable; however, in part (ii) of the theory, which describes the experience of sentient beings, FAPP is good enough by definition.

Instead of using other interpretations to state the connection in MWI between the branch wavefunction and experience in the corresponding world, I suggest an independent definition. I do not start from the ontology but from the concept of sentient beings. My definition, Vaidman (2021), is

> A world is the totality of macroscopic objects: stars, cities, people, grains of sand, etc. in a definite classically described state.

"The definitive classically described state" is well defined in the framework of classical physics. We think and communicate using classical concepts, so since "world" is our concept, the definition is rigorous. However, it is not rigorous in the framework of exact sciences. Classical physics is an approximation. Quantum physics, on the other hand, does not have a well-defined counterpart of "definite classically described state".

I have two alternative approaches to make the connection between wavefunction and definite classical state, see Vaidman (2019, 2022). Both are based on 3D structures. First, an observation: the Heisenberg uncertainty principle – which states that we cannot have a definite position and velocity of an object – does not provide a measurable constraint on macroscopic objects. I can live all my life with an uncertainty of less than a picometer in the position of my body's center of mass. So, position variables of macroscopic bodies can be described as extremely well-localized wave packets.

The first approach to make the connection is to specify the values of macroscopic variables, such as centers of mass, of macroscopic objects. The variable describing my position does not have to be center of mass; it can be, instead, the average of the positions of all the particles of my body, although the center of mass has an advantage as it can play a role in some conservation laws. To specify the state of my body, I also need to know the relative positions of the macroscopic parts of the body and their orientations. These are also described by well-localized coordinates. There is no entanglement in the world's wavefunction for these macroscopic variables. There are many relative variables with entanglement: relative positions of electrons within atoms, positions of atoms within molecules, and possibly positions of molecules within cells. Many of these entangled wavefunctions are definite energy states, such as internal relative states of particles in atoms.

The second option is fully geometrical. There is no need to look for observables that describe the position and state of the body – just the 3D graph of the mass density or the graph of the particle density. (Mass density is often considered as a primitive ontology Allori et al. (2014). However, I think this move adds nothing since mass or particle densities are not contingent properties for a given wavefunction.)

We identify objects according to their shape in 3D. In fact, the identity of elementary particles and the impossibility of keeping the diachronic identity of elementary particles when they meet particles of the same kind at a beamsplitter change the classical concept of an object. I am not a set of elementary particles that make up my body. I am a particular pattern of the wavefunction of these particles. Of course, it should be the wavefunction of degrees of freedom of the "correct" type. If all electrons in my body were replaced by protons and all protons by electrons, then it would not be me. This modified "me" will have a shape resembling me for an astronomically short time. This Gendanken situation resembles a Boltzmann brain, which I would not consider as my brain even if it has momentarily the same shape.

The importance of 3D follows from the dynamical property of our universe belonging to part (i) of our theory. All interactions are local in 3D. The general Hamiltonian formalism of quantum mechanics allows all types of interactions. The locality of interactions is the property required by the theory of relativity. There is a similar property in part (ii). In our everyday life, interactions are local in 3D. You read these lines when the book or monitor is near you. I model the experience of sentient beings as memories of preparations of measurements and memories of results of measurements. Here, a famous observation of David Bohm (which was one of the motivations for Bohmian mechanics) is relevant: all measurements end up being measurements of position in 3D, either it is the position of the pointer of your ammeter, or a pixel of the digital readout of another measuring device. The 3D feature in part (ii) follows from the property that sentient beings are local and that they have local senses, but of course, the analysis of the evolution that created local sentient beings has its roots in the locality of dynamical interactions of part (i).

Although there is a huge conceptual difference between the ontology of the Bohmian effective collapsed wave function of all particles and the Bohmian positions of all particles, the 3D picture of them is very similar. Bohmian positions do not "sit" at the centers of the wave packets of the particles, but these wave packets are localized so well that the global picture of all of them tells us the same story. Since for me, worlds are classically understandable stories, we have no difference here. Similarly, the von Neumann collapsed wavefunction, as well as the GRW or Diosi-Penrose collapsed wavefunctions, correspond to the same story. The difficulty appears in the MWI because the 3D graph of the mass density of the MWI universal wavefunction (without collapses) does not provide a picture of a familiar world. It is not supposed to provide such a picture, because it corresponds to a multitude of worlds.

I propose to postulate in my theory part (ii): the correspondence of the ontology to the experiences of sentient beings. Here, I deviate from the exact sciences: experience is not a precise concept. Other approaches add a new ontology trying to stay as much as possible in the realm of exact sciences; I understand the motivation but do not see a success: a good scientific theory that provides a familiar picture of the world we observe. My alternative approach is accepting existing physics, which is a very successful exact science theory, and adding an invariably vague postulate that connects the ontology of the exact theory to our approximate and vague concepts of experience. This should include a description of a sentient being, which is biology but also robotics, since, if not today, in the near future robots equipped with artificial intelligence will be considered FAPP as sentient beings as (or better than) humans. Since we are building the robots, we understand their behavior better than we understand ours, so it seems to be an easier task to understand the connection between the "experience" of the robots, which is just records of their sensory devices, and the ontology, the wavefunction.

We consider a robot with a classically designed brain (not a quantum computer). So, our classically defined robot in a world has, by definition, a classically defined sentient state. Part (ii) provides a correspondence between the wavefunction of the robot and its sentient state. If we describe the state of the robot using the position and orientation of its macroscopic parts, they all have to be well-localized wave packets. Or, if we define the state of the robot through the 3D map of its mass density, it has to be a precise "sculpture" of the robot.

In a hypothetical universe in which all that exists is a room with the robot and some objects that are not quantum measuring devices like Geiger counters, single-particle detectors, etc., the wavefunction of the room with the robot and the objects provides a good description of the robot and its experiences for a reasonable period of time. But it is clear that our universe is not like this, both because there are many more objects than the objects in the room and because there are many quantum devices that performed in the past and are performing now quantum experiments, including some natural phenomena like supernovae, which amplify the superposition of some microscopic degrees of freedom to the macroscopic level.

Does the universal wavefunction and the postulate of connection between part of the wavefunction and the experience of a sentient being provide a good explanation of what we see? The MWI is often presented in the following way. There is a universal wavefunction. The decoherence with the environment leads to the emergence of branches of the universal wavefunction that are autonomous and correspond to the experiences of sentient observers "living" in these branches. I would not say that this picture is wrong, but it has not been shown that the emergence program works. In my understanding, this picture is supposed to start with a hot universe at the Big Bang and show how decoherence creates stars, planets, people, and robots. Current physics explains extremely well the results of all experiments: regularities between preparations and outcomes. It is less successful (maybe yet) in explaining the history of the universe starting from its creation. One difficulty is that we only have very partial information about the state of the universe at the beginning. A lot of data is not near us now, and, more importantly, most of the data is present in parallel worlds, not in our world to which we have a direct access.

I am skeptical of giving a very important role to environmental decoherence. I know that we have to fight decoherence in quantum optics interferometric experiments, such as experiments in which I have been involved when I tried to give meaning to locations of quantum particles within an interferometer Danan, Farfurnik, Bar-Ad, & Vaidman (2013).

The usual claim is that decoherence ensures the autonomy of branches. The usefulness of this claim is less clear to me. The linearity of quantum mechanics ensures that each branch in the superposition is autonomous with or without environment.

If we start with a single branch with a robot in the room and no quantum devices, the typical dynamics will keep this single branch as the only one for a long time. Usually, the spread of wavepackets of macroscopic objects is very small. There will be some tails, but we can take a natural approach to disregard branches that have very small amplitude, i.e., have very small "existence" (the square of the amplitude of a branch I name the *measure of existence*).

I see one situation in which decoherence might help. If we start with a highly localized wave packet of the position of the robot, due to the uncertainty relation, the wave packet will spread very fast. Now, we can view the particles of the environment as measurement devices which verify with high frequency that the position of the robot remains localized (not localized with very small uncertainty, just well localized as most macroscopic objects are localized in the room). Then, the quantum Zeno effect will suppress the spreading of the wavefunction. However, we should not expect extreme position localization because the creation of a high-precision localization of a macroscopic body requires huge energy resources.

If spread is not an issue, then the role of decoherence is just spoiling the interference. But we do not expect to observe interference of macroscopic bodies anyway. This requires a technologically unthinkable experiment in which sentient beings in two different branches split into identical branches (with different relative phases). I once considered the Gedanken story with a sentient neutron Vaidman (1998). The experimentalists perform such experiments with neutrons Greenberger (1983). In a neutron experiment, decoherence changes the probability of a neutron being in different output ports. In fact, in a tuned interferometer, the neutrons without decoherence might be more surprised that their odds of passing a beamsplitter apparently changed (due to interference with a neutron from another "neutron" word). Anyway, it is not a dramatic change: It only puts a question mark on the validity of a statistical Born rule. The neutron cannot be sure that its behavior was not autonomous but was influenced by the neutron in the other world. Note that considering a neutron as a sentient being is only a Gedanken story (e.g., because it does not have enough internal degrees of freedom to be sentient), and for representative (macroscopic) sentient beings the interference experiment is not feasible, so the decoherence is not relevant for the absence of interference of macroscopically different worlds.

The concept of decoherence might be useful due to the observation that awareness states of sentient beings are stable under decoherence interactions. In my scheme, the question of why sentient beings (people, robots) are the way they are is not part of the interpretation. (We can investigate this question, and the locality of interactions in 3D will play an important role in this analysis.) Given the locality of sentient beings and the locality of the pointer states, the locality of interactions tells us that these states are stable. If $|G\rangle_{MD}$ and $|E\rangle_{MD}$ are two well-localized pointer states in two separate positions, then starting with any one of them we will continue to keep this state for a long period of time. If, instead, we start with the state (2), which is one of the nonlocal states $|\pm\rangle_{MD} \equiv \frac{1}{\sqrt{2}}(|E\rangle_{MD} + |G\rangle_{MD})$, then, due to decoherence, in no time ($t \ll 10^{-10}s$, see Joos & Zeh (1985)) we will get a mixture of $|+\rangle_{MD}$ and $|-\rangle_{MD}$ states. Thus, nonlocal states cannot serve the purpose of awareness states. However, again, decoherence is just an additional argument, which is not really needed. The complexity of the manipulation of nonlocal states required for information transfer and information analysis cannot be compared with the complexity of manipulating the local pointer states which are used in the robot's "brains" (and as far as we understand, in our brains too). So even if super-technology offered us to remove the environmental decoherence, we would probably not use robots with nonlocal awareness states. An exception is a special task machine, the quantum computer. There, indeed, we make a (big) effort to remove decoherence to allow running special programs that provide quantum supremacy.

I can summarize the discussion of part (ii) of the MWI, the correspondence between ontology and experiences of sentient beings, by stating two alternative postulates. To simplify them, I assume that we understand the operation of sensory devices well. This is certainly true for robots (we could not build them without understanding this), and apparently our sensory devices are not conceptually different. Then, instead of describing the state of the brain with particular experience, we can describe the states of macroscopic objects which sentient beings observe.

> An agent experiences a macroscopic object if all macroscopic variables defining the state and position of the object are well-localized wavepackets in the world branch of the wavefunction.

Or, an alternative postulate

> An agent experiences a macroscopic object if the 3D picture of the density of particles of the object calculated based on the world branch of the wavefunction faithfully represents the object.

Note that the branch of the wavefunction has to keep the pattern of the object for a reasonable time, so that the brain of the sentient being is capable of experiencing the object.

However, these postulates are not enough. Apart from observing classical objects, we witness quantum phenomena. There are superconductivity and superfluidity, which classical physics has difficulty explaining (together with the stability of atoms), but what is really different, are quantum measurements. The laws of classical physics cannot explain experiments with identical preparations that might have different outcomes. The randomness observed in quantum experiments and the statistics of the outcomes, which has no roots in the ignorance of some agent about initial conditions, is another kind of experience of sentient beings that requires an explanation. Fortunately, the ontology – the universal wavefunction – has parameters that played no role in explaining the observations of the classical picture. The branches with the same experiments but different results might have different amplitudes that play no role in describing the 3D patterns or the positions of macroscopic objects. These amplitudes explain the Born rule statistics of the experiments through the second postulate of part (ii), see Vaidman (2021):

> The probability of self-location in a world with a particular outcome is proportional to the measure of existence of this world.

The measure of the existence of the world is the square of the amplitude of the corresponding branch of the wavefunction. Apart from providing the probability of self-location in a world, the measure of existence of the world characterizes the power of interference of this world if a super-technology were to arrange an interference experiment with other world branches. I explained this in my Gedanken story of a sentient neutron inside a Mach Zehnder interferometer, Vaidman (1998).

I view the postulates of part (ii) of the MWI as part of the theory. While the first postulate (in both forms) is very natural (it is a “duck test”), the probability postulate is more substantive. Essentially, it is the counterpart of the Born rule of collapse theory in MWI. Since, in the framework of the MWI, all possible outcomes of quantum measurements are realized, we cannot define the Born rule in a usual form. There is no meaning to the probability of obtaining a particular outcome in a measurement when all outcomes take place. We also cannot ask what outcome a particular agent will see: she will split into multiple agents, with everyone seeing some outcome. The MWI has no diachronic identity of an agent toward the future. So, to state the probability postulate, we need a special arrangement (sleeping pill experiment **?**) which will lead to *different* agents that are not aware of who they are, in which world they are, i.e. what is the measurement outcome in their world (although they might know all relevant aspects of the ontology of all worlds).

Note that there are multiple “derivations” of the Born rule in the framework of the MWI: Gleason (1975); Deutsch (1999); Aharonov & Reznik (2002); Wallace (2007); Zurek (2005); Vaidman (2011); Sebens & Carroll (2018). I have argued Vaidman (2020) that all have some explicit or implicit assumptions beyond the quantum formalism of part (i). Many of these assumptions are very natural, e.g. Vaidman (2011) assumed symmetry of space and impossibility of superluminal signaling, but without any assumptions, the Born rule cannot be derived.

The mathematical part describing the constraints and the evolution of the ontological (physical, mathematical) part of the theory, which I named part (i), leaves an important part (the Born rule) undefined. Outside of the framework of the MWI, the Born rule belongs to the physical part of the theory. It is an important postulate, but apparently due to the recent quantum information technology revolution, it has received disproportionate attention. Usually, when we ask the question what is the probability of a particular choice among a set of possibilities, we find many situations in which we have reasons to consider all possibilities equally probable, and then a simple counting provides a good answer. If all branches, actual in MWI, or possible in single-world theories, are similar (their measures of existence must be equal), then simple counting will provide the correct answer in the quantum realm, too.

Part (i) of my MWI is ontological, while part (ii) is epistemic. Usually, ontological interpretations start with what is and derive an ontic picture that is very close to our experience. The Bohmian positions of atoms of a duck have the shape of the duck, the Bohmian positions of atoms of wings of the duck change in time as flapping wings change their position in time, the oscillation of Bohmian positions of air molecules looks like sound waves, so the ontic picture of Bohmian positions explains our experience. Epistemic interpretations start with experience and do not necessarily try to answer questions about what exists (see recent review Barzegar & Oriti (2024)); the theory describes experience in terms of the state of knowledge of sentient agents. In relational approaches to quantum mechanics, Rovelli (1996); Zwirn (2023), for example, quantum theory is a theory of information, where information is subjective to agents. Thus, in Bohmian mechanics we start with the ontology of the universe, which includes Bohmian positions of an agent who has her experiences, while in relational approaches the universal picture does not exist: the experience of an agent is described by her relations to other objects.

Today, a popular (frequently named Oxford) approach to the MWI is finding emerging worlds with their agents with particular experiences by analyzing decoherence in the universal wavefunction. So, it is an ontological approach like the Bohmian one which, however, leads to multiple worlds (instead of one) with agents whose experiences are explained by the theory. This route has to solve a difficult problem that Bohmian mechanics apparently does not have. How to get separate worlds that do not interfere with one another? Bohmian mechanics has one world, so the question usually does not arise, although, in fact, Bohmian mechanics has essentially the same problem. There are "empty" worlds with "empty" wavepackets, which, in principle, can affect the actual Bohmian world. This would happen for a neutron world in a Mach-Zehnder interferometer without the second beam splitter in which neutrons follow "surrealistic trajectories", Englert, Scully, Süssmann, & Walther (1992). (Note that we cannot really get an experimental proof that Bohmian trajectories exist Vaidman (2024a).) Coming back to Oxford school of MWI, I find that the analysis of evolution from the Big Bang which leads to emergence of worlds of the type we know is a difficult problem that requires complicated physical analysis in cosmology, etc. We also have very limited information about the current universal wavefunction because we know very little about parallel worlds. Thus, I do not suggest starting the analysis from the universal wave function.

I observe that there are situations in which the world splitting is clear: when we perform quantum measurements, like creating a single photon and detecting it after it passes a beam splitter. The Geiger counter clicks also split the world, although it is more complicated as we have to understand what is the time difference between the clicks which makes the worlds different. So my proposal is to start from our world. My world is not an ontological concept (it exists for me but not for my copies in parallel worlds). So, what I propose is a hybrid approach. I start with the epistemic part (ii). My experience and my knowledge of my world give me information about the corresponding branch of the wavefunction. My memories of quantum experiments that have been performed in my world also give me some information about a few parallel worlds. I believe in their existence and in the existence of all the other worlds about which I have almost no information because I believe that there is an ontological theory for the whole universe that evolves according to physical laws of the same type as the laws that explain all experimental data we observe in our world. The laws we know are deterministic Vaidman (2014) and have no action at distance Vaidman (2024b). To explain my experience, on top of the ontological story of the unitary evolution of the wavefunction of the universe, I need again the epistemic part (ii) with the almost obvious connection between myself and the wavefunction of my particles in my branch, which looks like and sounds like me, and a natural probability postulate which has numerous supporting arguments, but no derivation from part (i).

In conclusion, physics explains all phenomena we observe on Earth extremely well. Collapse of a quantum state at measurement is an ugly scar on a beautiful quantum mechanics. The only role of the collapse is to avoid parallel worlds which anyway are not supposed to be seen according to the theory. Without collapse we have to accept MWI. Apart from the disappointment in understanding that I am not a unique Lev Vaidman, and that there are multiple copies of me in other worlds, MWI allows me to believe that by and large I understand how the universe works. For me, parallel worlds are not a too high price to pay for understanding Nature.

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