Wave function realism and three dimensions

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Abstract It is argued that our experience of life in three-dimensional space can be explained by an ontological picture of quantum mechanics consisting solely of the wave function of the universe formally defined in the configuration space. Our experience supervenes on a part of the universal wave function which is defined in three dimensions, while the other parts (defined in configuration space) explain physical properties of objects. A deterministic universe without action at a distance requires the acceptance of the existence of parallel worlds similar to our world.

1 Introduction

The foundations of quantum mechanics are still far from consensus and the meaning of its basic concept, the wave function, continues to be under heated debate. I consider the quantum state, the wave function of the universe, to be the only ontology of quantum theory [1,2]: "All is Ψ". In parallel, we witness an extensive discussion of the term wave function realism [3]. In this paper I want to clarify my approach and put it in the context of the current discussion.

There are many different meanings of realism. My experiences are real, but the word "real" does not have the same meaning as in the expression "wave function realism". Our "real" experiences supervene on the physical ontological reality. In my semantics, ontology describes substance, matter. I separate it from nomological entities (like the Hamiltonian) which specify how the ontological description of the universe changes in time.

In physics, realism is frequently considered as local realism, which has two aspects: separability and local causality. Separability: the combined complete local descriptions of all space points provide the complete description of reality. Local

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causality: objects can influence other objects only when they are physically close together. The locality (or nonlocality) of quantum physics is the main question to be discussed here.

Once, the realistic picture of the world was the following: There is a three-dimensional space (3D). In this space there are local macroscopic objects: people, animals, stones, trees, etc. interacting locally among themselves. These interactions explain the time evolution: changes in the form and position of the objects in space. A cat has to reach a mouse to eat it.

Although the development of classical physics, in an attempt to reach a deeper understanding, encountered difficulties – Newton worried that the gravitational interaction between objects is apparently nonlocal – at the end of the nineteenth century classical physics seemed to be very close to reaching a satisfactory picture: particle-field realism. The fundamental ontology consists of point particles moving in space affected locally by fields. All objects are made of atoms (stable configurations of nuclei and electrons) which have fundamental interactions among themselves by the local creation of fields which propagate in space and then locally affect other particles. Not only familiar macroscopic objects move and interact in 3D, but also the microscopic objects move and interact in the same space.

However, the success of classical physics was illusory. The stability of atoms and other objects, together with many other phenomena, had no explanation within classical physics and it was replaced by quantum physics. Quantum mechanics explains the stability of atoms, existence of rigid bodies and (apart from gravity) all our observations. It has an extraordinary success: there is no discrepancy between what can be calculated and what is measured. In some cases the agreement is up to ten decimal numbers.

The quantum solution was achieved by introducing ontology which is very different from the ontology of classical physics: there are no particles moving on trajectories in 3D. The particle realism of classical physics is replaced by the wave function realism. The wave function is defined in the configuration space of N particles (in a simple case of nonrelativistic quantum mechanics). The route to explain our experience based on this ontology [4, 5] is not simple and this is apparently the reason why the approach encounters skepticism [6, 7]: how one can see in an abstract quantum state, a complex valued wave function in the configuration space, the familiar objects in 3D? I suggest accepting the fundamental role of 3D from the beginning. Macroscopic objects, as well as microscopic objects, interact in 3D. The role of 3D was not questioned in classical physics since there was no need for the configuration space to provide complete ontological description. Quantum mechanics needs the configuration space, but only for quantum effects rarely seen in everyday life. Macroscopic objects reside and interact in the familiar three dimensional space.

2 The single world universe

Consider a naive understanding of the textbook (von Neumann) view [8]. Everything, including measuring devices, is described by the wave function. The wave function evolves locally and unitarily, until it evolves toward a superposition of macroscopically different states of a macroscopic object, when it collapses nonlocally to a wave in which all macroscopic objects are well localised. A similar picture is given by the Pearle-Ghirardi-Rimini-Weber collapse theory (commonly known as GRW) [9, 10] in which a concrete physical (but ad hoc) proposal replaces a vague postulate of "well localised macroscopic objects". In this (frequently collapsing) wave function we can see a realistic picture of the world. Local macroscopic objects: people, animals, stones, trees, etc. interact among themselves locally in 3D, changing their form and position in space.

We do not know the precise expressions for wave functions of macroscopic objects, they have too many ($> 10^{20}$) degrees of freedom. In classical physics we would have a similar difficulty, but we can gain understanding by considering simpler, smaller systems, because there is no conceptual difference in the behaviour of microscopic and macroscopic systems: particles, as macroscopic objects, move in 3D and interact locally (directly, or through the creation of and interaction with local fields) between themselves. This move, however, is not available in quantum physics. The wave function of a microscopic system does not collapse to a well localised state, so the analysis of the behaviour of microscopic systems does not provide proper understanding of the behaviour of macroscopic systems.

Macroscopic objects, due to their large mass and moment of inertia, can have a well defined position, orientation, and other variables describing their macroscopic properties changing slowly enough to explain the time evolution of our perceived world. The way to express this is to describe the world wave function as a product of quantum states of all macroscopic objects $|\Psi_{\text{object j}}\rangle$ times the state of the remaining particles $|\Phi_{\text{rest}}\rangle$ which do not belong to any macroscopic object.

$$|\Psi_{\text{world}}\rangle = \prod_j |\Psi_{\text{object j}}\rangle |\Phi_{\text{rest}}\rangle. \tag{1}$$

The wave function of every object is a product of wave functions of collective variables, describing the macroscopic properties of the object, times entangled wave functions of its microscopic constituents:

$$|\Psi_{\text{object}}\rangle = \prod_n |\psi(A_n)\rangle |\psi(b_1, b_2, ..., b_{N_b})\rangle |\psi(c_1, c_2, ..., c_{N_c})\rangle ... |\psi(o_1, o_2, ..., o_{N_o})\rangle. \tag{2}$$

Examples of macroscopic variables A_n are: the center of mass of the object, center of charge of the object, variables describing orientation of the object, electric and magnetic dipoles, quadrupoles, etc. These are the variables which appear in the Hamiltonian of the interaction with other macroscopic objects, so these are the variables describing how we perceive the object. These variables describe the object in 3D.

Entanglement appears in the wave function of microscopic constituents of macroscopic objects described by variables $b_j, c_j, ...o_j$. Start with an atom. It is a composite system of a nucleus and electrons. A stable atom, say, an atom in its ground state, exhibits a highly entangled state of its electrons. A piece of a solid body consists of ions and electrons (at this level ions can be considered as elementary units described by their own degrees of freedom without introducing degrees of freedom of their constituents). The electrons are in a complex entangled state which explains rigidity and other properties of the object. Ions (depending on the temperature) might be (or might not be) in a product state.

We might have entangled states of microscopic systems even if they are not responsible for the rigidity of a macroscopic object. A sealed can with a gas definitely has entangled states of gas molecules due to collisions between them. What we observe is the total action (pressure) of a large number of molecules together, which is essentially independent of the entanglement. Possible decoherence with external systems does not result in measurable differences.

Another way to see the 3D reality in the wave function of a world is to draw a "cloud" of expectation value of mass density in 3D, or cloud of atom density, etc. The geometric structures of places where these densities are significantly larger than the background (say, due to air) provide the familiar 3D pictures of objects. The mass (or matter) density is sometimes considered as the "primitive ontology" [11]. I do not see an advantage in defining this new ontology: the 3D cloud is the property of the already defined ontology, the wave function. Moreover, in some cases mass density might not be useful. If I only observe the 3D distribution of mass density, I will not be able to distinguish my body from the water in a swimming pool. The 3D picture of the density of organic molecules will distinguish me from the surrounding water. Thus, the wave function ontology describes our observed reality also in cases when the mass density ontology does not.

The true complete story of the world must include fields: this is how Newtonian nonlocal gravitational interaction becomes local: a massive object creates a gravitational field, the field propagates in space and affects the motion of other local objects. Moreover, the complete picture must also include the creation and annihilation of particles. Modern research (especially the deadlock of quantum gravity) suggests that we should go even further. It seems that Wallace [7] considers this as the main reason why wave function realism is not the correct picture. However, I feel that the road to an exact precise and complete story will not bring new conceptual philosophical difficulties and, on the other hand, it also will not provide the solution to the quantum foundations controversies. Moreover, it seems that we can simplify our consideration by neglecting relativistic effects and approximate the interaction between particles by forces described by potentials depending on the relative distances. This simplifies tremendously the analysis of the interaction between particles by removing the necessity of the separate treatment of fields created by the particles. Thus, I can follow Albert [12] by modeling the world as a (large and constant) number N of quantum particles. For simplicity, I do not discuss the important issues related to the wave function of identical particles (fermions, bosons).

The state of the world of N classical particles is fully specified by the position and velocity of each particle in 3D. Mathematically, we can represent it as the position and velocity of a single point in the configuration space of $3N$ dimensions. Moving to this representation seems very strange and not useful. Motion of this point fully represents evolution of all objects made out of classical particles, but in a very indirect way: the configuration space does not look like "space" as it is defined in Wikipedia or Britannica:

> **Space**, a boundless, three-dimensional extent in which objects and events occur and have relative position and direction.

Albert does not suggest using configuration space in the case of classical particles, however, he argues that we have to do it for the case of quantum particles. A quantum particle is not described by a point moving in 3D, but by a wave function changing in time in 3D. N noninteracting particles can be described by N wave functions in 3D, but the interaction between particles invariably leads to entanglement between the particles and thus N 3D spaces are not enough to describe the state of N quantum particles. The wave function in the configuration space is. This is the reason why Albert considers the configuration space of N particles as the fundamental space.

Ney [5] finds support for this picture because it avoids the non-separability following from entanglement if we consider the particles separately. However, avoiding separability by moving to another space does not seem helpful. It is the non-separability between objects, the non-separability between spatial regions of 3D, which is problematic. Even if the nonseparability persists in the high-dimensional configuration space, it does not represent a serious weakness. We do not expect properties of familiar 3D space to be present in an abstract configuration space.

Albert [4] argues that the connection to the perceived 3D comes from the dynamics defined by the Hamiltonian of our world. This program is similar to the approach which starts with an abstract Hilbert space of the universe and attempts to derive the emergence of the three dimensional picture we observe. The key element of the programs of deriving 3D is locality of interactions in 3D. In my view, this fundamental feature justifies the postulate of 3D. Familiar macroscopic objects are certainly present in 3D and we should try to find their ontological three-dimensional representation. Entanglement is invariably present among particles, and it prevents their description in a set of 3D spaces, but macroscopic objects we perceive are not entangled, so they do "have relative position and direction" in 3D.

Every set of entangled constituents of a macroscopic object does require a description in the configuration space, but the sets of constituents of different macroscopic objects are separate, and there is no entanglement with other objects. Macroscopic objects consist of sets of entangled microscopic objects. There can be a hierarchy of sets. Sets of entangled quarks make protons and neutrons. Sets of entangled nucleons make atomic nuclei. Sets of entangled nuclei and electrons make atoms... At some level, we get sets of systems which are not entangled with anything else. The collective variables of every such set of systems have well defined positions and directions in 3D. These positions are not exact, as they are described by well localised wave functions which cannot be localised too well to allow well localized conjugate momenta of these variables, necessary for avoiding fast changes of the positions and orientations. For everyday macroscopic objects, this constraint is not expected to be seen. The Heisenberg uncertainty for position and momentum of a person allows his localization to be smaller than 10^{-10} meters during all his life.

Our perception of macroscopic objects supervenes on the wave functions of the collective variables of microscopic constituents of these objects, the wave functions in 3D. The complete description of a macroscopic object involves entangled states of its constituents defined in their configuration space. A more detailed description involves entangled states of even smaller systems, the set of which makes the microscopic systems described above. And so on. At the top of the hierarchy are the wave functions of macroscopic objects in 3D. Thus, it seems legitimate to view this picture as a wave function realism in 3D. Albert's wave function realism in 3*N* dimensional configuration space is a more fundamental description, but clearly it is also not *the* fundamental description, there are several levels of more fundamental theories.

There is a long-winded way of recognising the familiar three dimensional objects from the wave function in the configuration space. This process heavily relies on the Hamiltonian of the world. By contrast, the role of the Hamiltonian in my picture is to explain changes in our experience, but not the experience itself. Imagine that Mephistopheles changes the Hamiltonian of the world when Dr. Faust says to the Moment flying: "Linger a while – thou art so fair!" such that the current wave function of the world becomes an eigenstate of the Hamiltonian. A minute later, Mephistopheles switches the Hamiltonian to be as it was before. I postulate that we all will have one minute of unchanging (beautiful) experience. We will not remember it, so it is not clear what is the operational meaning of this statement, but it provides a consistent definition which is apparently absent in Albert's picture. This demonstrates that there is no contradiction between the two approaches, the two pictures are similar, but built up in a different way. Three dimensional reality is a derived property of Albert's approach while it is a fundamental basis of my approach.

3 The many-worlds universe

Although I asserted above that the wave function realism describing *N* quantum particles can be upgraded to a more precise and complete quantum theory of relativistic fields without conceptual changes, I did not mean that this is true for a collapsing wave function. The collapse of the wave function includes genuine randomness and action at a distance, and because of this it does not fit with the standard picture of physical science.

Consider a particle in an equal amplitude superposition of two spatially separated wave packets. Our decision to measure or not to measure the presence of the particle in one location affects the wave function at another location immediately (for von

Neumann collapse) or in a very short time (in the GRW model) irrespective of the distance between the two wave packets. Indeed, if we decide not to measure the particle in one location, the wave function at another location does not change. The probability of the GRW jump of the wave function of an isolated single particle is very small. If however, we perform a measurement which entangles the presence (absence) of the particle in one location with two macroscopically distinct positions of a pointer consisting of a macroscopic number of particles, in a very short time the GRW hit of one of the particles of the pointer will cause a random change of the amplitude of the second wave packet from $\frac{1}{\sqrt{2}}$ to a number close to 0 or 1.

Even if the wave function is not the ontology (contrary to the approach taken here), this example demonstrates an action at a distance. Measurement in one location changes the situation in another location: without the first measurement, there is a genuine uncertainty about the result of the measurement in this location. Immediately after the first measurement, the result of the measurement in the remote location is deterministic.

Removing collapse makes quantum theory sensible from the physics point of view. The theory becomes deterministic [13] as a default required from a scientific theory [14], and it avoids an action at a distance. Why then was the collapse invented to be a part of quantum theory? Quantum theory without collapse apparently contradicts our empirical evidence that a quantum measurement ends up with a single outcome. There is no contradiction here, and it seems that Schrödinger [15] and maybe other fathers of quantum theory understood this, but the inescapable consequence of quantum theory without collapse – the existence of parallel worlds – was and still is difficult to accept.

The wave function of the universe is not given by (1). It is a superposition of the wave functions of the form (1):

$$|\Psi_{\rm universe}\rangle = \sum_i \alpha_i |\Psi_{{\rm world}_{\rm i}}\rangle. \tag{3}$$

Since a world i, and thus the quantum state of the world $|\Psi_{{\rm world}_{\rm i}}\rangle$ is not rigorously defined, the decomposition (3) is not rigorously defined too. One property of the decomposition is specified. The worlds are macroscopically different, ensuring the mutual orthogonality of various terms. Note that one of the terms in (3) might correspond to an unstructured microscopic systems, i.e. it might have no macroscopic objects. Even this world, at least formally, fulfills the definition: there are no macroscopic objects in a superposition of macroscopically different states.

You, the reader of this paper, live in a particular world corresponding to one of the terms, $|\Psi_{{\rm world}_{\rm j}}\rangle$ of the decomposition (3). If you adopt the Copenhagen or a physical collapse interpretation, you assume that this term is all that there is, $|\Psi_{\rm universe}\rangle = |\Psi_{{\rm world}_{\rm j}}\rangle$. This assumption clearly simplifies the task of finding the correspondence between our experience and the formalism of the physical theory on which our experience supervenes, but such a physical theory is hard to accept. A much nicer physical theory tells us that the ontology of the universe is described by the superposition (3).

The many-worlds interpretation (MWI) restores the 3D picture of the world with the single outcomes of quantum measurements we experience by postulating that we and other macroscopic objects exist only within a single world. Our experience supervenes on the wave function of one of the worlds $\Psi_{\mathrm{world_i}}$ exactly in the same way as it was described in the section about the single-world universe. The (only) ontology in quantum theory is the universal wave function (3), but what is relevant for our experience is one term of the universal wave function $|\Psi_{\mathrm{world_i}}\rangle$ corresponding to the world we live in. Both Ψ_{universe} and $\Psi_{\mathrm{world_i}}$ are defined in configuration space, but $\Psi_{\mathrm{world_i}}$ can also be written in the form of the product of wave functions of sets of particles corresponding to macroscopic objects and the wave function of the set of remaining particles, see (1). Each wave function of the set of particles corresponding to a macroscopic object can be written as a product of wave functions of various variables of the set, including collective variables defined in 3D, see (2). These wave functions are well localized and they describe familiar macroscopic objects. The interaction of macroscopic objects one with the other is fully specified by their descriptions in 3D. This is the way to answer Maudlin's worry [6] that the wave function of the universe defined in $3N$ configuration space is not appropriate for describing our familiar objects in 3D.

The explanations of properties of macroscopic objects like conductivity, rigidity etc. are based on the analysis of their microscopic ingredients, including entanglement of microscopic systems, which requires the configuration space. We also need the configuration space for the description of microscopic systems in quantum information tasks like teleportation, secure communication, etc. However, the configuration space is not needed for the explanation of the macroscopic behavior of macroscopic objects.

A popular view is that we need decoherence with the environment [16] to explain why the existence of parallel worlds does not alter our experience in a particular world. I, however, fail to see the relevance of the environment. An observer living in world j has the same experience with or without the presence of parallel worlds $i \neq j$. The quantum states of other worlds are macroscopically different and, therefore, it is not feasible to expect interference between the worlds. In principle, such interference can happen when world j splits into several worlds and at least two of them will appear from the splitting of some other world i, but due to macroscopic differences between worlds i and j we have no technological means to arrange such an experiment and the probability that this happens without our intervention is negligible.

Let us analyze an example. A Geiger counter is placed near a weak radioactive source such that it clicks on average once in ten seconds. A runner waits for the first click after 12 AM to start running on a 100 meter circle. There will be numerous worlds differing by the observationally distinguishable times the runner starts running. There is no precise definition for observationally distinguishable, although we do have a bound: the worlds should correspond to orthogonal states. Until now we introduced only one splitting (at Geiger click), so the terms in the superposition will not interfere due to unitarity. The runners will have an overlap in space, since there will be time differences of the take off between the worlds, but even if the centers of mass of the runners will be exactly in the same place, corresponding quantum states will be very different. To observe an interference, we need a very special situation in which additional splittings lead to creation of identical states from different branches. The decoherence due to the environment is irrelevant for the suppression of the interference, because macroscopic objects cannot (without unrealistic super-technology) exhibit the interference anyway.

The program of deriving the emergent classical world from the universal wave function [17], i.e. the derivation of the decomposition (3), is conceptually close to Albert's approach: start with fundamental $3N$ configuration space and argue that the Hamiltonian describing fundamental interactions leads to the 3D structure. The emergence program might be difficult: it is hard to start with the wave function of the universe and recognize the world we see around. Try to find the superposition of the runner from the complex entangled states of particles smeared around the running circle. It is also not clear how helpful the emergence program is. We do not know much about the wave function of the universe which includes all the worlds. But a more modest task is not problematic. We can reconstruct the relevant parts of the universal wave function to explain *our* world. We need to accept the existence of other parts (corresponding to parallel worlds) for having an attractive (simple, deterministic and without action at a distance) physical theory.

I presented here my preferred concept of a world [18] in which all macroscopic objects are well localized in 3D and thus the wave function of macroscopic variables of these objects is defined in 3D. Note that there is a legitimate alternative to the concept of a world in the MWI, closer to the original proposal of Everett [19] which can be understood as a subjective world of an observer. Only he, and all objects he is in contact with, are well localized. Measuring devices (e.g. Schrödinger's cat) which are not in contact with the observer are in a superposition of macroscopically different states after remote measurements (the meaning of this is clear, even if the semantics is forbidden according to my approach). In this alternative, the configuration space is needed not only for constituents of macroscopic objects, but also for macroscopic objects which are not in contact with the observer. The same argument for the necessity of the configuration space is even stronger if we consider the wave function of the universe which includes all the worlds. Still, the 3D space is important as it is the space of the fundamental interactions.

4 Our world

We see a single world. It is not difficult to imagine that there are other worlds like ours in remote galaxies, but that there are parallel worlds here, in the same place, is counter-intuitive. We see our one world and, naturally, are looking for a theory which will tell us how our world evolves. The MWI tells that our world evolves into multiple worlds, it definitely happens at every quantum measurement, but maybe it happens much more often [20]. We experience only a single world at any moment of time, so it is understandable that we are reluctant to accept existence of our copies.

What is even harder to accept is that the natural question: "What will be my world in the future?" makes no sense.

Understanding that our world often splits should change the paradigm of a world. We should accept that the picture of an evolving world is incorrect: there is no concept of our world line evolving towards the future: the world line becomes a tree which does not correspond to our (single) experience.

There is nothing in the MWI which points to the connection of a world in the past to a particular world in the future. However, we *can* follow our world line backwards in time. Every world has a history as a single world at every moment in the past. (We disregard here in principle possible, but not feasible, situations of merging worlds in experiments of super technology such as Wigner's friend experiment [21].) This past world line is what we have in our memories now and this is what led to the paradigm of the world evolving forward in time.

This provides the possibility to consider a forward evolving world. We can consider the time reversal of the well defined backward evolving world as the time evolution of our world. This world does not follow the laws of physics which are relevant to all worlds together. This "evolution" is not unitary and it includes an action at a distance. It is identical to the evolution of the textbook (collapsing wave function) world. This is the world which allows description of essential features of macroscopic variables (in particular their interaction with other macroscopic objects) by wave functions in 3D in product with entangled states of microscopic constituents of these macroscopic objects required for explanation of the rigidity, the conductivity and other properties of the objects, see (2).

Let us look more carefully at the wave function of our world. Apart from the wave functions of collective variables of macroscopic objects $\psi(A_n)$ represented by wave functions in 3D, the entangled wave functions in configuration space $\psi(b_1, b_2, ..., b_{N_b})$ of the constituents of macroscopic objects described in (2), there is an (in general entangled) wave function of microscopic systems which are not entangled with macroscopic objects, signified by $\Phi_{\rm rest}$ in (1). We do not experience directly these microscopic systems and usually there is no need to discuss their state. We do not directly experience also details of states of many microscopic constituents of macroscopic objects. Thus, it is natural to describe our world, as humans did a long time ago, by specifying only states of macroscopic objects. However, today, at the time of the quantum information technology revolution, it is sometimes important to describe quantum entangled states of microscopic systems in various experiments: single particle interferometry, teleportation, quantum key distribution. These particles are not well localized in 3D and, moreover, we need at least small parts of the configuration space to describe their entanglement.

I argued above that decoherence is not important in the MWI, but the *lack* of decoherence of microscopic particles is important. Then, between preparation and measurements, microscopic systems are described by the coherent superposition of macroscopically different states, including wave packets at remote locations. Between measurements, these superpositions either remain approximately constant or evolve in a known unitary way. The results of all measurements specify completely these states. So, one can choose to consider these results as an ontology. This does not seem to be an attractive option for ontology. Anyway, here we discuss the wave function as an ontology. The world wave function is not a complete ontology (the wave function of the universe is), but to explain our experience in our world, the world wave function is the relevant one. Our world is the world in the past which for every moment includes both preparation before this moment and postselection to our particular world after this moment. So, the complete description at every moment has, in addition to the standard forward evolving wave function, the backward evolving wave function specified by the measurement after this moment, see [22]. This description with two wave functions evolving forward and backward in time is relevant only for microscopic systems, because only for microscopic systems can these wave functions be macroscopically different. Within a world, by definition, there are no superpositions of macroscopically different wave functions of macroscopic objects.

Usually, we do not experience directly microscopic objects, so the two wave function description is important only for understanding quantum experiments. I find it useful because it provides a new consistent (and surprising) picture of the reality of pre and post-selected quantum systems. Microscopic objects can be assigned positions in 3D, but in contrast to the classical behavior of macroscopic objects, they might not necessarily follow classical continuous trajectories: they can leave (weak) traces simultaneously in several places [23] and these traces have a complex structure [24].

In a single world universe, the connection between experience and the wave function is very natural: there is one experience and one wave function. In the many-worlds universe, the situation is more subtle. If the wave functions of worlds are different only in their distant locations, such that we have only one wave function of particles corresponding to the observer, we have only one observer with a particular experience. But consider a situation in which I performed a quantum measurement and it is arranged that I am moved slowly in a closed chamber to different locations according to the results of the experiment [25]. After the experiment, there are several Levs, each aware of parts of the wave function corresponding to all Levs and each having the experience of being in a chamber. My wave function corresponds to my experience, but in which chamber am I? Another postulate about the probability of self-location (that it is proportional to the measure of existence of the world with the corresponding result of the experiment) is needed (see more details in [26]).

5 Summary: three dimensional aspects of universal and world wave functions

Wave function realism is a thesis that the only ontology of Nature is a pure quantum state without additional or alternative primitive ontology [27] (e.g. beables [28]) in 3D. The wave function of the universe by itself has an intimate connection to the 3D space, although formally it is not defined in 3D. The source of the connection is that the fundamental interactions take place in 3D which leads to the following explanation why we experience life in 3D.

Our experience supervenes only on one of the terms of the superposition (3), our world wave function. In my semantics, in every world all macroscopic objects are well localised in 3D and every world wave function describes full 3D space including remote galaxies. (I do not enter cosmological issues of the size of the universe.) In a world wave function every macroscopic object is described by a well localised wave function in 3D in a product state with a (usually entangled) state of their constituents, states of other macroscopic objects, and (possibly entangled) states of microscopic systems which do not form what we might describe as a macroscopic object.

Our experience supervenes only on the part of the world wave function in 3D near us, so the same “we” live in multiple worlds which differ by locations of remote macroscopic objects. We can split our worlds locally by performing quantum experiments. Do it right now with the help of the Tel Aviv Worldsplitter [29]! There is no meaning to asking in which world we will be after the splitting, but we can ask what was our world in the past. During the whole history of our world (at least not too close to the Big Bang) our world had macroscopic objects well localised in 3D.

In our world it might be of interest to assign locations in 3D to some microscopic objects, e.g. a single photon passing through an interferometer. Note, that when its forward and backward evolving wave functions are different, the evolution of these locations might not behave in a classical way [23].

I suggest a direct connection between our experience and our world wave function, recognising our three-dimensional picture in the world wave function by, for example, drawing a three-dimensional map of the density of the wave function of human tissue cells. This is instead of arriving at our experience through operators, e.g., awareness operators [30].

Although the universal wave function is not defined in 3D, it has a very important property in 3D: there is no action at a distance. Disturbances cannot propagate with superluminal velocity. If we consider the time evolution of two universal wave functions which differ at a particular time only in a localised 3D region, they might differ in the future only in the regions that the light starting at that time from the localised region can reach. The universal wave function is nonlocal in 3D in the sense that it is nonseparable, so I have to explain exactly what is the meaning of local differences. If a system C in a remote location is entangled with a system A near me, I can, by a local swap operation, change the entanglement of the remote system C to another system in my location. However, the complete local description (given by the local density matrix) in remote locations (the locations the light cannot reach) cannot be changed.

The wave function of a particular world has different 3D properties. Remember the way we consider the time evolution of a world. At a particular time, based on our records of events (results of quantum measurements in the past), we reconstruct the forward evolving (collapsing) wave function. To formulate action at a distance we consider two situations in which we reconstruct world wave functions in a particular time in the past which are different only in a localised 3D region. Since world wave functions evolve in a non-deterministic way, there (most probably) will be local differences in remote locations. But if the difference is a change of a setup which specifies the measurement in the local region on a particle entangled with a system in a remote location, we can be certain that there will be differences between the two world wave functions in the regions the light cannot reach. Within a particular world, there is an action at a distance in 3D. We can affect the local description of remote microscopic systems. On the other hand, in the world wave function we have separability in the 3D of the part of the wave function describing macroscopic properties of macroscopic objects. There is no entanglement between macroscopic objects. They all are described by the product of localised wave packets in 3D (times the quantum states of their constituents).

The majority of physicists view quantum theory as a great success. They all say that the wave function collapsing at measurements explains in an excellent way all that we see around. They accept the postulate that our experience supervenes on this wave function. It is the Collapse with its action at a distance and randomness that goes against the spirit of physics. What I tried to explain here is that we do not need Collapse. The wave function, instead of collapsing, splits into macroscopically different world wave functions. Every one of these world wave functions explains well the experience of life in 3D.

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