Nothing happens in the Universe of the Everett Interpretation

Jan-Markus Schwindt

E-mail: jan.schwindt@googlemail.com

Abstract

Since the scalar product is the only internal structure of a Hilbert space, all vectors of norm 1 are equivalent, in the sense that they form a perfect sphere in the Hilbert space, on which every vector looks the same. The state vector of the universe contains no information that distinguishes it from other state vectors of the same Hilbert space.

If the state vector is considered as the only fundamental entity, the world is completely structureless. The illusion of interacting subsystems is due to a "bad" choice of factorization (i.e. decomposition into subsystems) of the Hilbert space. There is always a more appropriate factorization available in which subsystems don’t interact and nothing happens at all. This factorization absorbs the time evolution of the state vector in a trivial way. The Many Worlds Interpretation is therefore rather a No World Interpretation.

A state vector gets the property of “representing a structure” only with respect to an external observer who measures the state according to a specific factorization and basis.

1 Introduction

The Everett Interpretation (EI, also known as Many Worlds) \[1, 2, 3\] is in a sense the minimal interpretation of quantum mechanics (QM): It basically claims that only the state vector \(\psi\) of the universe and the global Hamilton operator \(H\) are fundamental. Everything else follows from the dynamics given by the Schrödinger equation. In particular, the state vector does not represent the state of some objects. It is the object itself.

According to the EI, there is no mysterious collapse of the state vector, no hidden variables, no split between a classical and a quantum realm (Heisenberg cut), no fundamental randomness. A measurement is - like many other processes - a process in which a subsystem entangles with its environment. The dynamics is such that the global state
vector is (roughly speaking) split into branches, one branch for each possible result \( a \) of the measurement:

\[
|\Psi_{\text{before}}\rangle \longrightarrow |\Psi_{\text{after}}\rangle = \sum_a c_a |\Psi_a\rangle
\]  

(1)

Each branch then evolves independently, constituting a kind of “separate world” (hence the name Many Worlds Interpretation). The split is, however, only an apparent one; in fact the state vector remains a single state vector. This is a reason why \(|\Psi\rangle\), in this context, should not be considered as being the state vector of some separately existing objects: These objects would really have to split when the state vector branches, and this “ontological excess” would make the EI unattractive.

The EI is very attractive for several reasons:

- It makes a minimal number of assumptions, and postulates a minimal number of entities (only \( H \) and \(|\Psi\rangle\); the branches are not separate entities, they are parts of \(|\Psi\rangle\) and arise naturally through the dynamics).

- It demystifies the measurement process. A measurement is a quantum interaction like anything else. This view is supported by the theory of decoherence, which shows that entanglement and branching are totally natural in interactions of a subsystem with its environment.

- It is closer to our traditional understanding of science, because of its intrinsic determinism and realism.

The EI also has a burden, which comes with the small number of assumptions and entities: It needs to explain how the world that we experience emerges from it, in particular the classical behavior on macroscopic scales on one hand and the appearance of probabilities in quantum measurements on the other hand.

The two most serious and most discussed problems of the EI are these:

- How can the EI explain the observed probabilities in quantum measurements? I.e., why is the squared norm \( |c_a|^2 \) of a branch equivalent to the probability an observer encounters for measuring the value \( a \)? If an observer performs the “same” (equivalent) measurement many times, the state vector branches each time, and in the end there will be a branch for each combined result of the measurements. Each branch also contains one version of the observer. Each observer will conclude the probability for each value \( a \) from the statistics of the individual results he got. One can show that the norm of the part of the state vector corresponding to branches where observers don’t get the right probabilities converges to zero when the number of measurements is increased \([2]\). The remaining question is whether or not this argument solves the problem (I think it does). In this paper, I will not deal with the probability problem, so I won’t discuss this issue any further.

- The branching in eq.\((1)\) occurs only with respect to a specific basis. How can we determine this basis from the dynamics? This is referred to as the basis problem.
The basis problem consists of two parts:

(A): How can the universe be split into subsystems appropriate to the measurement? I.e., how can the measurement device $M$ and the system $S$ to be measured be singled out within the global $|\Psi\rangle$? In other words: How can we split the global Hilbert space $\mathcal{H}$ into a tensor product

$$\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_M \otimes \cdots$$

such that the factors represent what we see as the “objects” of the measurement? There are no “real” objects, but the apparent objects must be somehow justified as properties of the evolving state vector.

(B): What is the basis of $\mathcal{H}_S$ and $\mathcal{H}_M$ along which the branching happens?

The second part is solved by decoherence [4, 5, 6]: Once the factorization into subsystems has been done, the interactions of $S$ with the environment (of which $M$ is a part) lead to branching according to a specific basis, and in each of these branches, $M$ will show a specific result.

The really tough part is (A). One purpose of this paper is to show that it is the hard problem of the EI. I will refer to it as the factorization problem.

It is interesting that the factorization problem has received so little attention. Most authors focused on the part of the basis problem which is solved by decoherence. Only few authors have noticed that the factorization problem is a serious threat to the Everett interpretation [3, 7, 8].

I think the reason is mainly that in almost all situations occurring in practice, the subsystems are already given (particles, cats, ...). The tensor product is considered bottom-up, from the subsystems to the total system, not top-down, from the total system to the deduction of an “appropriate” decomposition into subsystems.

Wallace [9] has claimed that the whole basis problem is not an issue, because it is not necessary to specify a basis for the EI to work. The choice of a basis in QM is like the choice of a sequence of spatial “constant time” hypersurfaces in General Relativity (GR). It is up to the user to define such hypersurfaces in order to solve a problem. But the physics of GR is independent of such a choice, and GR works without the requirement of such a choice to be specified.

I totally agree with Wallace that the analogy should be valid if the EI works. The only problem is that in GR there are frame-independent quantities, like the Ricci scalar, or the square of the Riemann tensor. So we can, independently of a choice of coordinates, decide whether two given manifolds have the same properties or not. The state vectors in QM, however, are all equivalent. The only structure internal to $\mathcal{H}$ is its scalar product. Taking only the state vectors of norm 1, there is no structure available to distinguish them. They form a perfect complex sphere, and every vector looks the same. This turns out to play a central role for the factorization problem, and to be a challenge for the EI.
I want to give two analogies to the argument I am presenting here:

1. **Minkowski space:**
   As a vacuum solution of GR, Minkowski space describes an empty universe without curvature in which nothing happens. It is described, in an appropriate coordinate frame, by the line element
   \[ ds^2 = -dt^2 + dx^2 + dy^2 + dz^2 \]  
   But, using a different coordinate frame, we get the line element
   \[ ds^2 = -\tilde{dt}^2 + \tilde{t}^2 \left( \frac{d\tilde{r}^2}{1 + \tilde{r}^2} + \tilde{r}^2 d\Omega^2 \right). \]
   This is still Minkowski space, but in this frame it looks like it is an expanding universe with negative spatial curvature. And of course we can construct much worse spatial hypersurfaces, in which Minkowski space looks like there are all kinds of spatial structures evolving in time.

   I will call a frame like that of eq.(3) a **Nirvana frame**: a frame in which it is obvious that nothing happens. A frame like that of (4) will be called **Samsara frame**: a frame in which it looks like something happens, although in fact nothing happens\(^1\). My argument will be that in the EI, bases which show a branching are just Samsara frames. We can always find a Nirvana frame which shows that in fact nothing happened at all.

2. **Classical Phase space:**
   In classical mechanics, Hamilton-Jacobi Theory tells us that for each system it is possible to find a canonical transformation such that the generalized position and momentum variables \(Q_i, P_i\) are constant. This constitutes a Nirvana frame of phase space. Nothing ever happens in this frame. Every classical system has “Nirvana character” in such a generalized phase space. If phase space were the **only real thing, the fundamental stage of physics**, one may ask why one should ever consider coordinates different from those of the peaceful Nirvana frame. But in classical mechanics, we use this generalized version of phase space only as a **tool** to describe the motion of the **real particles** which move through a three-dimensional space and have **real positions** \(q_i\) and **real momenta** \(p_i\), and the generalized \(Q_i, P_i\) are useful only because we can express \(q_i\) and \(p_i\) as functions of them. Alone and intrinsically the \(Q_i, P_i\) have no meaning and cannot have one, because they describe, in an appropriate frame, a universe in which nothing happens at all. I will argue that the same is true for the state vector \(|\Psi\rangle\) of the universe.

   Section 2 contains an outline of the EI, and a list of things that need to be explained from the dynamics of \(|\Psi\rangle\) if it is really fundamental. The factorization problem and its implications are discussed in detail.

In section 3 I will argue that \(|\Psi\rangle\) **per se** (without the help of distinguished operators acting on distinguished subspaces) contains no information at all, and that it is easy to choose

\(^1\)These terms are used as a purely metaphoric analogy to certain ideas from Indian philosophy. I’m *not* trying to suggest a real connection between physics and such a philosophy.
a basis where $|\Psi\rangle$ describes a structureless universe in which nothing happens. In section 4, a simple measurement process is discussed. It is shown that the branching explanation of the process via entanglement and decoherence works only bottom up but not top down. I.e., if a factorization of the Hilbert space is already given, we can describe the interactions within that factorization (i.e. between the chosen subsystems) and get a branching that happens in the full Hilbert space according to a preferred basis within that factorization, the “decoherence basis”. But if one starts from the full Hilbert space and the dynamics of the full state vector, it is possible to find a different factorization in which there are no interactions at all between the new subsystems. The conclusion (section 5) is that if $|\Psi\rangle$ were truely fundamental, choosing a basis in which the world has a structure is like choosing a coordinate system in which Minkowski space is an expanding universe. To render QM a senseful theory, one has to provide a distinguished factorization of the Hilbert space, based on entities other than $|\Psi\rangle$. Or one has to give up the idea of a universal $|\Psi\rangle$ altogether. Possibilities and consequences are discussed. Finally (section 6), the relation of the argument to other work in physics and philosophy is discussed.

## 2 The Everett Interpretation and the factorization problem

The postulates of QM provided by a typical textbook are:

1. The state of a quantum system $S$ is described by ray of vectors in a complex Hilbert space $\mathcal{H}$. Usually one represents the state by a normalized element $|\Psi\rangle$ of the ray (called the state vector), $\langle\Psi|\Psi\rangle = 1$.

2. To each physical observable belonging to $S$ corresponds a hermitean operator $A$ acting on $\mathcal{H}$. In a measurement
   
   (a) the measured value $\lambda$ is an eigenvalue of $A$;
   
   (b) the state $|\psi\rangle$ of the system gets projected onto the eigenspace corresponding to $\lambda$ (“collapse”);
   
   (c) the probability for obtaining $\lambda$ is $\langle\psi|P_\lambda\psi\rangle$, where $P_\lambda$ is the projection on the eigenspace.

3. The time evolution of a state $|\psi\rangle$ is determined by a Schrödinger equation

\[
\frac{d}{dt}|\psi\rangle = H|\psi\rangle
\]

where $H$ is the Hamilton operator representing the observable which measures the system’s energy.
The claim of the EI is essentially that only postulates 1 and 3 are fundamental, while postulate 2 arises as a consequence of 1 and 3, on a subjective level, i.e. as the impression gained by an observer performing a series of measurements.

The description of a measurement given by the EI is claimed to be as follows: A measurement is a QM process that is completely covered by the dynamical evolution of the state vector $|\Psi\rangle$ of system + measurement device + observer + environment, according to the Schrödinger equation. (The Hilbert space in which this state vector lives is the tensor product of the Hilbert spaces corresponding to each of the items). The Hamilton operator contains interaction terms which enforce an entanglement of the system with the measurement device, and further with the observer and the environment. As a consequence, $|\Psi\rangle$ is (approximately, in an appropriate basis) split into several branches, i.e. a sum of terms, where each term corresponds to one possible result of the measurement. Each term contains the state of an observer who thinks he has projected the state of the system according to a hermitean operator. But in fact, no projection has taken place, only an entanglement, and the only hermitean operator acting was the global Hamilton operator.

There are a number of things the EI has to explain if it is supposed to be the correct stage for QM:

- **Factorization:**
  How does the appearance of objects arise? I.e., why is it “natural” to factorize the global Hilbert space into a tensor product of Hilbert spaces, such that each factor makes sense to us as the Hilbert space of an object we can distinguish from the rest of the “world”, where the “world” is an arrangement of many such objects. This is the factorization problem mentioned in the Introduction. Given that there are infinitely many possibilities to factorize a Hilbert space $\mathcal{H}$ (unless the dimension of $\mathcal{H}$ is a prime number): Why is there a choice that is distinguished by describing the “objects” of our “world”? The preferred choice must somehow arise from the state vector and its dynamics. It must be a choice that lets the state vector or its time evolution appear in a particularly simple way, or that lets the dynamics of the chosen subsystems appear as independent as possible, or something alike.

Tensor factorizations can be constructed in the following way: If the dimension of $\mathcal{H}$ is a finite number $n = pq$, choose a basis and label the basis vectors with double indices, $\{|e_{ij}\rangle\}$, where $i$ runs from 1 to $p$, $j$ from 1 to $q$. Then write

$$|e_{ij}\rangle = |f_i\rangle \otimes |g_j\rangle$$

and consider the $\{|f_i\rangle\}$ as a basis of subsystem S1, the $\{|g_j\rangle\}$ as a basis of subsystem S2. This defines the subsystems. If $p$ or $q$ is non-prime, the factorization can be continued. If the dimension of $\mathcal{H}$ is infinite, one or both of the indices can be chosen to run from 1 to $\infty$. Some choices $\{|e_{ij}^{(1)}\rangle\}$ and $\{|e_{ij}^{(2)}\rangle\}$ are equivalent in the sense that the transformation between them is only a transformation within S1 and S2.
separately, i.e. they both correspond to the same split of the entire system into two subsystems, only the basis for those subsystems is different. But for most choices, the split into an S1 and an S2 will be truly different. I will refer to \( \{ |e_{ij} \rangle \} \) as the factorization basis.

Are we allowed to choose the factorization in a time-dependent way? With time-dependent \( \{ |e_{ij}(t) \rangle \} \)? Since \( |\Psi \rangle \) depends on time, and we are discussing subsystems that arise as “meaningful” from its time dependent behavior, why should we not allow these emerging subsystems to move their “position”/“orientation” within the global Hilbert space? (With subsystems I mean the Hilbert space factors, not the corresponding factors of the state vector.) This is also reasonable if one wants to keep a certain equivalence between the pictures of QM. A picture is a vector identification map (VIM) that tells us which state vector in the Hilbert space at time \( t_2 \) is “equal” to a state vector in the Hilbert space at time \( t_1 \). In the Schrödinger picture, the state vector evolves according to the Schrödinger equation; in the Heisenberg picture, it does not evolve at all, i.e. the state vectors are identified along their trajectory. If a factorization is constant in the Schrödinger picture, it will in general not be constant in the Heisenberg picture, and vice versa. Deutsch [3], for example, in his approach to the EI, discusses everything in the Heisenberg picture. His factorizations have to depend on time, because otherwise no entanglement could happen. The state vector is constant, so the only way how it can represent the process of entanglement between interacting subsystems is when its decomposition is not constant. If we want to keep the pictures on equal footing, we should also allow for time dependent decompositions in the Schrödinger picture. However, one may argue that in the EI, the Schrödinger picture is singled out: The dynamics should happen in the state, not in the operators, because operators are not fundamental [6]. Still, even when the Schrödinger picture is preferred, I don’t see any principle that forbids subsystems to change their “position”/“orientation” in the global Hilbert space.

Some comments about the time evolution of the subsystems’ states are in order. The Hamilton operator (here for the generic case of an explicit time dependence) can, for a given split into two subsystems, be decomposed

\[
H(t) = H_1(t) \otimes 1 + 1 \otimes H_2(t) + H_{\text{int}}(t),
\]

and then, because there are infinitely many ways to write \( H(t) \) in such a form, one may choose the one in which \( H_{\text{int}}(t) \) is, at each time, “minimal” in a certain sense I will not specify any further. Again, this is an unusual task, because usually the subsystems, their internal Hamilton operators and their interaction are already given. Here, the decomposition of \( H(t) \) defines the interaction. If (a) the factorization is constant, i.e. \( \{ |e_{ij} \rangle \} \) does not depend on time, and if (b) \( H_{\text{int}}(t)|\Psi(t)\rangle \) is zero for some time interval, and if (c) \( |\Psi(t)\rangle = |\psi_1(t)\rangle \otimes |\psi_2(t)\rangle \) at the beginning of that time interval, then each subsystem state will evolve independently according to a Schrödinger equation with Hamilton operators \( H_1(t) \) and
If the factorization is not constant, i.e. \( \{|e_{ij}(t)\}\) does depend on time, there may still be time intervals in which the subsystem states evolve independently. The evolution is still unitary, so each subsystem state will appear under the effect of a Schrödinger equation. The corresponding “apparent” Hamilton operators, however, are not the operators \( H_1 \) and \( H_2 \) of the decomposition (7) any more. Part of the time dependence was brought in “by hand”, via the time dependence of the factorization, and that part cannot be derived from the global Hamilton operator \( H(t) \).

• Space:
  How does the appearance of space arise? The state vector lives in an infinite or very high dimensional complex Hilbert space. Why do the “objects” look like they are layed out in a three-dimensional real space? Sure, the state \( |\Psi\rangle \) was constructed as a wave function \( \Psi(x_1, \ldots, x_{3n}) \) (if we restrict ourselves to the QM of \( n \) scalar particles moving in three dimensions for a moment); and the Hamilton operator \( H \) was contructed in this spatial basis too, and is, with respect to its symmetries, most clearly written in the spatial basis, i.e. written as an operator acting on wave functions. The state vector will in general not have the same symmetries as \( H \), just as in general a solution to some equations of motion doesn’t have the symmetries of the equations. (The symmetries of the equations are reflected as symmetries between different solutions, not as symmetries within one solution.) Basically \( |\Psi\rangle \) is an abstract vector that appears as a wave function if we write it in a spatial basis. But why does an observer, who arises as a certain part of the state vector, see his “world” of “objects” layed out in a space which corresponds to this specific basis? (Here, “part” means something like a factor in a certain branch of \( |\Psi\rangle \), possibly after “tracing out” practically inaccessible degrees of freedom of the environment. I will not discuss the possible complications in defining an observer in the EI, because it is not the main concern here. For example, “tracing out” implies that one considers a density operator instead of a state vector, i.e. the observer is involved in some kind of ensemble picture, which I want to avoid here.)

In fact, there are infinitely many different spaces that can serve as a basis. (When I say a space “serves as a basis” I mean that all vectors of the Hilbert space are written as wave functions in \( n \) copies of that space, where \( n \) is the number of particles). Consider the case \( n = 1 \), and two orthogonal state vectors \( |e_1\rangle \) and \( |e_2\rangle \) of norm 1. Written as wave functions in some “\( x \)-space” (in which \( H \) takes a particularly simple and symmetric form), we may have

\[
\langle x|e_1 \rangle = f_1(x), \quad \langle x|e_2 \rangle = f_2(x)
\]

(8)

where \( f_{1,2} \) are specific functions which are orthogonal to each other. We may define a new space, “\( y \)-space” via

\[
\langle y|e_1 \rangle = f_2(y), \quad \langle y|e_2 \rangle = f_1(y),
\]

(9)
and for all vectors $|e_i\rangle$ which are orthogonal to $|e_1\rangle$ and $|e_2\rangle$, we define

$$\langle y|e_i\rangle = \langle x = y|e_i\rangle,$$

(10)

where $\langle x = y|$ is the (pseudo-)vector for which $x$ has the same value as $y$ on the left hand side of the equation. That is, in $y$-space the roles of $|e_1\rangle$ and $|e_2\rangle$ are exchanged. In terms of $x$-space, the vector $|e_1\rangle$ represents the function $f_1$; in terms of $y$-space, the same vector represents the function $f_2$, and vice versa for $|e_2\rangle$. For all vectors orthogonal to $|e_1\rangle$ and $|e_2\rangle$, the corresponding functions are the same in both spaces. This is always possible because there must be a unitary transformation which exchanges $|e_1\rangle$ and $|e_2\rangle$ and leaves all vectors orthogonal to them invariant. The relations (9) and (10) define the new space. The two spaces are totally different. You don’t get $y$-space by simply moving around some points of $x$-space. And yet we can write $|\Psi\rangle$ as a wave function in $x$-space or in $y$-space, and there is no reason why $|\Psi\rangle$ should look simpler in $x$-space than in $y$-space. (This is well known for $x$-space versus $k$-space, the Fourier transformed space. This is just a reminder that there is an infinity of such spaces.) The Hamilton operator will look very unpleasant in $y$-space. The position operator $X$ looks nice in $x$-space and unpleasant in $y$-space. The position operator $Y$ looks nice in $y$-space and unpleasant in $x$-space, etc.

So, the question is: Why do we appear to live in the space in which the Hamilton operator looks particularly simple? Does the time evolution of $|\Psi\rangle$, induced by this Hamilton operator, also have particularly nice properties if expressed in that space? (We will see that this is not the case.)

In quantum field theory (QFT) things are more complicated, but not qualitatively different. The Hamilton operator is constructed as an integral over operators (operator-valued distributions) which are local with respect to some $x$-space. So, $x$-space takes part in the construction of $H$. But we can refer to $H$ as an abstract hermitean operator acting on the global Hilbert space, without referring to how it was constructed. Again, $H$ may take on its simplest form if it is written in terms of such an integral. But again the question is why an observer, arising as some part of the global state vector, “sees” this particular space over which the integrals run.

The question of how space arises can be considered a part of the factorization problem. If the distinguished factorization is such that the Hamilton operators $H_i$ of the subsystems $S_i$ still have their simplest form if written in $x$-space (i.e. as operators acting on wave functions in $x$-space), and the interaction Hamiltonian $H_{\text{int}}$ between the subsystems describes interactions local in $x$-space, then we have a good reason to consider $x$-space as distinguished. There are more complications, for example how to identify the $x$-spaces of the subsystems with each other. In what sense can we say that the $x$-space in which $S_1$ is expressed is the “same” space as the $x$-space in which $S_2$ is expressed? Intuitively it seems reasonable that the answer is somehow contained in the local interaction again. The interaction gets strong when the $x$-value of $S_1$ gets close to the $x$-value
of $S_2$ (if both $S_1$ and $S_2$ are in states such that their wave functions are narrow in $x$-space, so that we can speak of an “$x$-value of $S_{1,2}$”). In that sense we may say that $S_1$ gets “close” to $S_2$. Again, I will not go any deeper here.

- **Classicality:**
  Why do the “objects”, in particular if they are macroscopic, appear to have classical properties? I.e., why don’t we see any superpositions, objects smeared out in space etc? These questions can be asked only if the previous issues have been resolved, so we know what the objects are and what space is. But then these particular questions are resolved by decoherence. The interactions carry the superpositions of an object into the environment via entanglement, such that the superposition is, after a short time of interaction, a global superposition, i.e. a branching structure of the global state vector, instead of a local superposition just within the object. Within a branch, the object appears to have classical properties, in the sense that the properties which are distinguishable through the interactions have definite values within a branch.

- **Measurement:**
  How does the second postulate of QM emerge from 1 and 3? This is also resolved by decoherence. A measurement is a controlled interaction between a measuring device $M$ and a system $S$. The interaction is such that a certain property of $S$ is distinguished, i.e. the different components of $|\Psi_S\rangle$ with respect to a specific basis of $\mathcal{H}_S$ have a different impact on $M$. This leads to a branching of the global state vector where in each branch only one component of $|\Psi_S\rangle$ survives. Together with the value shown by the pointer of $M$ this gives an observer (who lives in one branch) the impression he has projected $|\Psi_S\rangle$ with a specific hermitean operator. The appearance of probabilities is still under discussion, but as mentioned in the introduction a reasonable solution exists.

From the discussion in this section we may conclude that the EI is a reasonable and elegant framework for QM **as soon as we can solve the factorization problem**.

## 3 The state vector of the universe

The factorization problem with all its implications, as described in the previous section, looks quite complicated. The solution is remarkably simple: Nothing of all this happens in the EI.

We have only two fundamental entities at hand: the state vector of the universe $|\Psi\rangle$, and the Hamilton operator $H$. We assume $H$ to be not explicitly time-dependent, because a time-dependent $H$ is hard to reconcile with the symmetries of special or general relativity, or with a global energy conservation. We may forget about how $H$ was constructed and consider it just as an abstract hermitean operator acting on $\mathcal{H}$, the space in which $|\Psi\rangle$ lives. The time evolution of $|\Psi\rangle$ takes the simplest form in the basis where $H$ is diagonal,

$$
|\Psi(t)\rangle = \sum c_n e^{-iE_n t}|n\rangle,
$$

(11)
where $|n\rangle$ are the eigenvectors and $E_n$ the corresponding eigenvalues (for simplicity we assume a discrete spectrum). Each component of $|\Psi\rangle$ peacefully performs its phase rotations. In this form, it seems hard to believe that $|\Psi\rangle$ describes interacting subsystems. Yes, $H$ was constructed as the operator of “energy” present in some interacting particles or fields. But how are these interactions represented in $|\Psi\rangle$? Not at all. At least not when we look at it in this simple form.

Now let’s discuss factorizations into subsystems. One may ask why the “peaceful” state (11) should be factorized at all. Let’s ignore the why-question and just do it. However, when we do it, we should look for factorizations as simple as possible. If we find a “Nirvana factorization”, according to which nothing happens, we should prefer it as compared to a “Samsara factorization”, according to which it seems like something happens; just as the Minkowski metric (3) should be considered more “appropriate” than (4). That is because a Samsara frame constitutes an arbitrary and unnecessary complication. Of course, both metrics (3) and (4) are correct. But if we ask: “Is Minkowski space associated with the prediction of an expanding universe?”, the answer should be no. Similarly, if we find a Nirvana frame for $|\Psi\rangle$, we can no longer claim that the EI predicts a universe in which subsystems interact and entangle with each other.

I will divide the following discussion into two parts: At first I will consider only time-independent factorizations of Hilbert space, then also time-dependent ones. As I discussed in the previous section, I think the second option is fine, but some people may be more conservative.

If a factorization has to be **time-independent**, one can proceed in two steps: At first one may look for a decomposition in which the subsystems don’t interact at all, i.e. the Hamilton operator can be written as

$$H = H_1 \otimes 1 \otimes 1 + 1 \otimes H_2 \otimes 1 + 1 \otimes 1 \otimes H_3 + \cdots$$

(12)

This is the case if all eigenvalues $E_n$ can be written in the form

$$E_n = E_1^{(1)} + E_2^{(2)} + E_3^{(3)} + \cdots$$

(13)

for some index sets $I, J, \text{etc.}$, $i \in I, j \in J, \text{etc.}$, such that all combinations $E_1^{(1)} + E_2^{(2)} + E_3^{(3)} + \cdots$ occur in the spectrum of $H$, with the correct degeneracies. (If the dimension of $\mathcal{H}$ is a finite number $d$, the product of the cardinalities of $I, J, \text{etc.}$ must be $d$.) Then we may relabel

$$|n\rangle = |ijk \cdots\rangle,$$

(14)

take this as the factorization basis,

$$|ijk \cdots\rangle = |i\rangle \otimes |j\rangle \otimes |k\rangle \cdots,$$

(15)

and interpret the $E^{(\alpha)}_i$ as the energy eigenvalues of the subsystems $S_n$. This is a Nirvana factorization, there is no interaction between the subsystems, and nothing happens except
phase rotations for each energy component, in each subsystem independently.

If such a decomposition does not exist, we may still relabel the \(|n\rangle\) in multiindex form, as in (14), but this time in an arbitrary way (consistent with the dimension of \(\mathcal{H}\), if that is finite), and use this as the factorization basis, as in (15). Now, there are interactions between the such defined subsystems. But their only effect is to cause different speeds for the phase rotations of the branches: The time evolution of \(|\Psi\rangle\) reads now

\[
|\Psi(t)\rangle = \sum c_{ij} \cdots e^{-iE_n(ij\cdots)t} |i\rangle \otimes |j\rangle \otimes \cdots
\]  

(16)

Each term in this sum can be interpreted as a branch of the world, according to the chosen factorization. But all branches are there right from the beginning, they are not due to some entanglement that happens in a physical process. Each branch peacefully rotates with its frequency \(E_n(ij\cdots)\), and nothing else happens. Therefore, we can still consider this a Nirvana frame.

If one allows time-dependent factorizations (and I think this is what one should do), the situation becomes even simpler. Now we don’t even have to assume that \(H\) is time-independent, and we don’t need to work with a discrete spectrum to keep things simple. We may just choose a time-dependent basis vector \(|e_1(t)\rangle\) which absorbs the time evolution of \(|\Psi(t)\rangle\),

\[
|e_1(t)\rangle = |\Psi(t)\rangle.
\]  

(17)

This means, we effectively move to the Heisenberg picture. If we take \(|e_1(t)\rangle\) as part of a factorization basis (the rest of the basis is irrelevant), i.e.

\[
|e_1(t)\rangle = |f_1\rangle \otimes |g_1\rangle \otimes \cdots
\]  

(18)

we have a real Nirvana factorization: In the subsystems according to this factorization, nothing happens at all, not even phase rotations. Each subsystem is in an eigenstate with respect to its “apparent” Hamilton operator, with eigenvalue zero. There are no branches and no interactions, \(|\Psi(t)\rangle\) is once and for all given by the tensor product (18).

This simple choice is possible due to two facts: (a) All state vectors of norm 1 are equivalent, there is no structure available in the Hilbert space which distinguishes \(|\Psi\rangle\) from any other state vector. It makes a difference with respect to \(H\), but who cares? Nobody is ever going to make a measurement on \(|\Psi\rangle\) using \(H\) (measure the “energy of the universe”). Instead, the EI assumes that everything follows from “inside” \(|\Psi\rangle\) and its time evolution. Yes, different \(|\Psi\rangle\)s have different time evolutions. But: (b) Since we have no other guiding principle how to choose subsystems of \(\mathcal{H}\), we can just choose them such that they absorb this time evolution for the given \(|\Psi\rangle\) in the most trivial way.

This is a fundamental property of Quantum Mechanics: The state vector per se does not contain any information at all. The information arises only when a state is measured using a specific operator. The presence of “information” or “structure” requires both,
the state vector and the operator. Here, “measured” can be understood either in the “mystical” sense of the Copenhagen Interpretation, or in the sense of entanglement + decoherence. In any case, there must be an environment to which the state vector really represents a state. For the state vector of the universe, there is no such environment.

The tensor product structure of Hilbert space is usually only considered bottom-up, not top-down. That is, one starts from a given product structure (system, environment) and given interactions, and computes the time evolution of this product structure. The combined state vector is always written as a vector in a tensor product of the subsystem Hilbert spaces. But for the EI to make sense, we have to go the other way: we have to start from the combined Hilbert space and factorize it in a meaningful way such that interacting subsystems emerge. In this section I have demonstrated that this does not work, or more precisely: We can factorize it into interacting subsystem, but the way to do this is unnecessarily complicated and completely arbitrary. In the next section I will discuss the bottom-up versus top-down problem by the means of a simple example.

4 The measurement process bottom-up and top-down

We base our discussion on an idealized simple measurement process. Consider a system $S_2$ consisting of a measurement device $M$ and an object to be measured, $S_1$, with corresponding Hilbert space

$$\mathcal{H}_{S_2} = \mathcal{H}_M \otimes \mathcal{H}_{S_1}. \quad (19)$$

For simplicity, we take $\mathcal{H}_{S_1}$ to be two-dimensional and $\mathcal{H}_M$ three-dimensional. We denote the basis vectors of $\mathcal{H}_{S_1}$ in which the measurement is diagonal $|\uparrow\rangle$ and $|\downarrow\rangle$. Before the measurement, $M$ will be in the state $|0\rangle$. After the measurement, $M$ will be in the state $|+\rangle$ if $S_1$ is in the state $|\uparrow\rangle$, or $|−\rangle$ if $S_1$ is in the state $|\downarrow\rangle$. Here, $|0\rangle$, $|+\rangle$ and $|−\rangle$ are orthogonal and can be thought of as pointer positions of the measurement device: $|+\rangle$ indicates that $|\uparrow\rangle$ has been measured, $|−\rangle$ indicates that $|\downarrow\rangle$ has been measured.

According to the Everett interpretation, the whole measurement process can be described by the unitary evolution induced by the Hamilton operator $H$ acting on the six-dimensional space $\mathcal{H}_{S_2}$. That is, $H$ contains an interaction term between $M$ and $S_1$ which lets an initial state $|0\rangle \otimes |\uparrow\rangle$ evolve into $|+\rangle \otimes |\uparrow\rangle$, and similarly for $|\downarrow\rangle$:

$$|\Psi\rangle_{\text{before}} = |0\rangle \otimes |\uparrow\rangle \longrightarrow |\Psi\rangle_{\text{after}} = |+\rangle \otimes |\uparrow\rangle \quad (20)$$

$$|\Psi\rangle_{\text{before}} = |0\rangle \otimes |\downarrow\rangle \longrightarrow |\Psi\rangle_{\text{after}} = |−\rangle \otimes |\downarrow\rangle \quad (21)$$

For simplicity we assume that

- the interaction is switched on at a time $t_{\text{before}}$ and switched off at $t_{\text{after}}$
- $|\Psi\rangle_{\text{before}}$ is constant before $t_{\text{before}}$
- $|\Psi\rangle_{\text{after}}$ is constant after $t_{\text{after}}$
The interaction is constant between \( t_{\text{before}} \) and \( t_{\text{after}} \), so \( |\Psi\rangle_{\text{before}} \) gets smoothly rotated into \( |\Psi\rangle_{\text{after}} \).

If we ascribe values to the pointer states \(+\rangle\) and \(\rangle\), say +1 and −1, then this time evolution generates the picture that \( M \) has “acted on \( S_1 \)” with a hermitean operator which in the chosen basis of \( \mathcal{H}_{S_1} \) has the matrix form \( \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \). This operator is a derived property of the process.

The superposition principle tells us that for an initial \( S_1 \)-state \( \sqrt{2} \left( |\uparrow\rangle + |\downarrow\rangle \right) \) the time evolution is

\[
|\Psi\rangle_{\text{before}} = \frac{1}{\sqrt{2}}(0 \otimes (|\uparrow\rangle + |\downarrow\rangle)) \rightarrow |\Psi\rangle_{\text{after}} = \frac{1}{\sqrt{2}}((+ \otimes |\uparrow\rangle) + (- \otimes |\downarrow\rangle))
\]  

(22)

Written in this form, the time evolution of \( |\Psi\rangle \) tells a Samsara story: The object \( S_1 \) entangles with the measurement device, thereby splitting \( |\Psi\rangle \) into two branches; one branch with measurement result +1, one with result −1.

We may choose the following orthonormal basis for \( \mathcal{H}_{S_2} \):

\[
|e_1\rangle = |0\rangle \otimes |\uparrow\rangle, \quad |e_2\rangle = |0\rangle \otimes |\downarrow\rangle, \quad |e_3\rangle = |+\rangle \otimes |\uparrow\rangle, \quad |e_4\rangle = |-\rangle \otimes |\uparrow\rangle, \quad |e_5\rangle = |+\rangle \otimes |\downarrow\rangle, \quad |e_6\rangle = |-\rangle \otimes |\downarrow\rangle.
\]  

(23)

(24)

Written in components according to this basis, the evolution given in (22) becomes

\[
\left( \frac{1}{\sqrt{2}}, -\frac{1}{\sqrt{2}}, 0, 0, 0, 0 \right) \rightarrow \left( 0, 0, \frac{1}{\sqrt{2}}, 0, 0, \frac{1}{\sqrt{2}} \right)
\]

(25)

Now we define

\[
|e'_1\rangle = \frac{1}{2}(|e_1\rangle + |e_2\rangle + |e_3\rangle + |e_6\rangle)
\]

(26)

\[
|e'_2\rangle = \frac{1}{2}(|e_1\rangle + |e_2\rangle - |e_3\rangle - |e_6\rangle)
\]

(27)

These two vectors can be completed by four other vectors to form another orthonormal basis of \( \mathcal{H}_{S_2} \). (The choice of the four other basis vectors is arbitrary, as long as they are orthonormal to the first two, because \( |\Psi\rangle \) has no components in their direction.) In this new basis, the time evolution in (22) becomes

\[
\left( \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0, 0, 0, 0 \right) \rightarrow \left( \frac{1}{\sqrt{2}}, -\frac{1}{\sqrt{2}}, 0, 0, 0, 0 \right).
\]

(28)

The story told by this encryption of \( |\Psi\rangle \) is a Nirvana story: \( |\Psi\rangle \) is a sum of two components. One of them is unchanged after the process, the other one acquires only a phase \( \exp(i\pi) \). There is no sign of any interaction or entanglement in this basis.

What happened? With the new basis we left the original picture of the six-dimensional Hilbert space \( \mathcal{H}_{S_2} \) being obtained from a tensor product. We considered it a space on its
own right, without reference to the tensor decomposition $\mathcal{H}_M \otimes \mathcal{H}_{S1}$ it was constructed from. This is in accordance with the Everett interpretation, where the larger Hilbert space is always more fundamental, and a meaningful tensor factorization should emerge from the dynamics in that larger Hilbert space. Then we constructed a basis in which the unitary time evolution operator $U(t_{after}, t_{before})$ is diagonal. In this basis the time evolution consists only of phase rotations of each component.

There are infinitely many possibilities to factorize a six-dimensional Hilbert space into the tensor product of a two- and a three-dimensional Hilbert space. Each six-dimensional basis can serve as a starting point to factorize the basis vectors similarly as in (23). For example, if we use $|e_1^\prime\rangle$, $|e_2^\prime\rangle$, … as a starting point, we may factorize

$$\mathcal{H}_{S2} = \mathcal{H}_{M'} \otimes \mathcal{H}_{S1'}$$  \hspace{1cm} (29)

by writing

$$|e_1^\prime\rangle = |0^\prime\rangle \otimes |\uparrow^\prime\rangle, \quad |e_2^\prime\rangle = |0^\prime\rangle \otimes |\downarrow^\prime\rangle$$  \hspace{1cm} (30)

e tc., which turns the evolution (22) into

$$\frac{1}{\sqrt{2}} |0^\prime\rangle \otimes (|\uparrow^\prime\rangle + |\downarrow^\prime\rangle) \rightarrow \frac{1}{\sqrt{2}} |0^\prime\rangle \otimes (|\uparrow^\prime\rangle - |\downarrow^\prime\rangle)$$  \hspace{1cm} (31)

No entanglement, no measurement takes place in this decomposition; the phase rotation of the $|\downarrow^\prime\rangle$ component is internal to $S2'$ and can be considered as being due to an $S2'$-internal Hamilton operator $H_{S2'}$. And yet it is exactly the same time evolution as in (22), only written in a different factorization of $\mathcal{H}_{S2}$.

The “Nirvana factorization” (29) tells a simpler story than the “Samsara factorization” (19). Why would one still choose the factorization (19) over (29)? The reason is, of course, that an external observer $O$ may be able to “read off” $M$, but not $M'$ (fortunately, since $M'$ wouldn’t tell him anything but “Nothing happened”). That is, he makes himself a “measurement” (observation) which operates on $\mathcal{H}_M$, not on $\mathcal{H}_{M'}$. The way in which the observer interacts with the system $S2$ sets a preference for

- the tensor decomposition (19), i.e. he sees the measurement device $M$ as a distinct object;
- the choice of basis for $\mathcal{H}_M$, i.e. he sees the state of $M$ as a choice between specific pointer positions.

Only due to this specific interaction with an observer outside of $S2$ the Samsara story of a measurement taking place becomes meaningful.

The problem is: We can play the same game again. According to the Everett interpretation, this new interaction can again be described by the unitary evolution of a state vector in a larger Hilbert space $\mathcal{H}_{S3}$, which is the tensor product of $\mathcal{H}_{S2}$ and the Hilbert space $\mathcal{H}_O$ in which the observer “lives”,

$$\mathcal{H}_{S3} = \mathcal{H}_O \otimes \mathcal{H}_{S2}. \hspace{1cm} (32)$$
The story given by this description is that of an observer entangling with the system $S_2$, splitting into a branch where the observer sees the measurement device in position $\ket{+}$ and another branch where he sees the measurement device in position $\ket{-}$.

Again, however, there is a basis of the combined Hilbert space $\mathcal{H}_{S_3}$ in which the unitary time evolution is diagonal. In this basis, nothing happens apart from phase rotations of some components. Applying the same argument as before, we see that the “Samsara factorization” into an observer and the System $S_2$ is a bad choice, because the according tensor split of the Hilbert space tells an unnecessarily complicated story.

We can go on like this, arguing that the system $S_3$ again interacts with its environment, in particular with other observers, who see the first observer $O$ as a separate entity, thereby favoring the original factorization. But at some point, we reach the state vector of the universe. Now there is no external interaction, no external observer anymore. At this point, there is no valid argument anymore why a Samsara factorization should be preferred, and the arguments of section 3 apply.

Some remarks:
1. A Nirvana factorization of $S_3$ can be obtained in analogy with $S_2$: Let $\ket{\Phi}_{\text{before}}$ and $\ket{\Phi}_{\text{after}}$ be the $S_3$-states before and after both the measurement has been performed and the observer has read off the result. Then define

$$\ket{\alpha} = \frac{1}{\sqrt{2}}(\ket{\Phi}_{\text{before}} + \ket{\Phi}_{\text{after}}), \quad \ket{\beta} = \frac{1}{\sqrt{2}}(\ket{\Phi}_{\text{before}} - \ket{\Phi}_{\text{after}}).$$

(33)

Since $\ket{\Phi}_{\text{after}}$ is orthogonal to $\ket{\Phi}_{\text{before}}$ (the state of $M$ after the measurement has no overlap with the state before the measurement), we can take $\ket{\alpha}$ and $\ket{\beta}$ as part of an orthonormal basis, and in this basis the time evolution is exactly as in (28), and we may factorize $S_3$ according to this basis.

In a less idealized measurement, without a definite $t_{\text{before/after}}$ where the interaction is turned on/off, and without perfectly orthogonal $\ket{\Phi}_{\text{before/after}}$, this way to define a Nirvana factorization does not work anymore. Instead, one has to follow the methods outlined in section 3.

2. Deutsch [3] has noticed the factorization problem and suggested a solution. He argued that if a measurement has taken place, there is a unique factorization in which certain nice properties hold for the subsystems $M$ and $S_1$; in particular, the time evolution looks like (22) in this factorization. Since there is only one such factorization, the factorization problem is solved, he claims. The flaws in his argument have already been demonstrated on a rather technical level in [10]. Now we see there is a really fundamental problem with his argument: The mere fact that a measurement (or an interaction) has taken place is already a property of the factorization, not of the state evolution. Deutsch erroneously considered the happening of a measurement a frame-independent property of the state evolution, and therefore suggested to look for a factorization which shows the entanglement most clearly.
3. The change from a factorization which shows interaction / entanglement into a factorization without interactions is applied in one very basic example of QM: the hydrogen atom. (The connection with our more global factorization problem has been pointed out already in [11].) The proton and electron interact with each other and make the hydrogen atom a two-body problem. It is, however, possible to disentangle the system into two independent one-body problems: one free system, given by a wave function of the center of mass position, \( \psi_{\text{cm}}(x_{\text{cm}}, t) \), and one system given by a wave function of the relative position of proton and electron, \( \psi_{\text{rel}}(x_{\text{rel}}, t) \), residing in a Coulomb potential. There is no interaction term between these two wave functions. This example is analogous to the disentanglement of the measurement process demonstrated in this section.

5 Conclusions

I have shown that it is always possible to factorize the global Hilbert space into subsystems in such a way, that the story told by this factorization is that of a world in which nothing happens. A factorization into interacting and entangling subsystems is also possible, in infinitely many arbitrary ways. But such a more complicated factorization is meaningful only if it is justified through interactions with an external observer who does not arise as a part of the state vector.

The Many World Interpretation is therefore rather a No World Interpretation (according to the simple factorization), or a Many Many Worlds Interpretation (because each of the arbitrary more complicated factorizations tells a different story about Many Worlds [7]).

We can say that the state vector of QM per se does not contain any information or substructure. The state vectors of norm 1 are all equivalent, because the scalar product is the only internal structure of a Hilbert space. Information arises only when a preferred basis is somehow singled out, according to which the state of the system can be written in components. (A part of the choice of basis is the choice of factorization, the split of the system into subsystems, which gives it an internal structure.) The information is then contained in the relation of the state to the basis, not in the state alone. The notion of information or structure which arises from this view is interesting and requires further discussion. Information or structure in this sense is not contained in an object, but only in the object’s relation to a receptor, or more precisely: the object’s relation to the way in which the receptor looks at the object. Another example in a very different context is discussed in section 6.2.

The state vector of the universe in the EI has no environment or observer it can relate to, and is therefore completely meaningless. The appearance of interacting subsystems of the universe are only due to a choice of a “samsara” basis, which is however completely arbitrary, just like a slicing of Minkowski spacetime is possible, which makes it look like an expanding universe (cf eq.4).

One has to add something to give the state vector and QM a meaning. First one can mention several things that will not help to solve the factorization problem:
1. Dynamical Collapse [12]: This is a modification of the Schrödinger equation to single out one of the “many worlds” dynamically. This has nothing to do with our concerns here and is not helpful at all. It leads only to a change of the time evolution of the state vector, which can again be absorbed by a comoving basis. The factorization problem is unaffected.

2. Postulation of spacetime: If spacetime is postulated as an additional entity, it becomes “natural” to construct the Hamilton operator from operators acting locally in space. But an observer would still have to arise from a substructure of the state vector (we didn’t postulate any additional objects in spacetime, only spacetime itself), and here is the problem: As discussed in sections 2 and 3, the state vector doesn’t “see” the space that went into the construction of the Hamilton operator. The factorization problem remains.

3. Dualistic interpretations of QM which emphasize the role of “minds”, like “Many Minds” [13, 14], or like interpretations which make mind responsible for a collapse of the state vector [15, 16]. In this case it is the burden of the minds to see the world according to a certain factorization. But since the state vector does not contain any structure at all, such an approach shifts all structure completely into the minds, or their reception of / interaction with the state vector, or the way in which the state vector guides the minds, or whatever is the appropriate terminology in a specific interpretation. I.e. all structure is pushed outside of what is in reach for scientific analysis. This cannot be regarded a meaningful solution.

There are several possibilities to avoid the factorization problem:

- **Pilot wave theory** (PWT), also known as Bohm theory [17, 18]: Particles moving in spacetime are added to the theory. i.e. a spacetime is postulated, and in addition particles moving in this spacetime are postulated. “Observers” consist of these particles, not of substructures of the state vector. The particles are “guided” by the state vector. Pilot wave theory has been criticized by EI proponents as unnecessary: The many worlds of the EI are also present here within the state vector, and the particles serve only as “pointers” to one of these worlds [19].

  But now we see that PWT solves the main problems discussed here: The particles define a meaningful factorization of the global Hilbert space (they are by definition the “objects”, i.e. subsystems of the universe), and a position space that serves as a preferred basis. The state vector is defined as a wave function in a configuration space corresponding to particle positions. The feature of the PWT, that it brings a preferred basis into the theory, is not a weakness, it is a strength. It remains to be seen, however, how well PWT can be adapted to a quantum theory as complicated as the Standard Model of Particle Physics.

- **Copenhagen Interpretation** (CI): The CI is actually a statement about science. The world as far as it can be described by science must be split into a realm of phenomena and a realm of modeling. The realm of phenomena contains subjects making observations on objects, and the objects are described in a “classical way” (on a first layer of modeling), i.e. with definite properties, and localized in spacetime. The realm of modeling (actually: the second layer of modeling) is a mathematical
structure (here: a Hilbert space) whose only purpose is to make predictions about the phenomena. It does not have an independent existence, and therefore there is no factorization problem. The question why there is a certain relation between the model and the phenomena, i.e. why the model actually predicts the phenomena, cannot be solved by science. The CI was often criticized as unclear and anti-realist. But one can also see it as a positive way to deal with the limitations of science. As an approach which accepts these limitations, and which makes the distinction between a model to describe phenomena and a model to predict phenomena (or their statistics) explicit; More comments on the CI and its relation to the EI follow in section 6.4.

• QM as an effective theory: QM is only a limit of a more fundamental theory. The state vector is therefore only an emergent object, not a fundamental one [20]. The appearance of interacting objects must be explained in the fundamental theory, not from the state vector.

6 Connections to other topics and Outlook

6.1 Epistemic versus ontic state

There is an ongoing discussion whether the state vector has “ontic” or “epistemic” character, where, roughly speaking, “ontic” means it is a real thing “out there”, and “epistemic” means it is just an effective way to characterize an observer’s subjective state of knowledge about a system.

One year ago, Pusey et al published a paper [21] which showed that certain interpretations treating the state vector as epistemic are inconsistent. (In particular, they showed that it is not possible to have a “real physical state” that is consistent with several quantum states, such that each of these quantum states can be interpreted as representing some subjective knowledge about the real state.) Here I have shown that the state vector also cannot be ontic, if “ontic” implies that it can stand by itself, without a relation to other objects or observers.

The strange hybrid character of the state vector comes from the fact that it makes sense only in relation to a measurement. On the other hand, it can describe the measurement process as part of itself, but only if the result is subjected to another measurement (as shown in section 4). I will come back to the strange double role of measurement in section 6.4.

In my opinion, the whole notion of ontology and its relation to science should be rediscussed with a fresh attitude. I will present some ideas in that direction in a separate paper.

6.2 Story of a Brain

An argument very similar to the one presented here has been given by Zuboff in his *Story of a brain* [22] to reject certain theories about how subjective experience arises
from brain states. These theories contained certain assumptions about which aspects of the brain states are irrelevant to the generated experience. From these assumptions Zuboff constructed transformations of the geometry and sequence of the firing / non-firing neurons, which should leave the experience unaffected. He was able to combine the transformations in such a way that finally the “brain” consisted of only one neuron which fires one single time. He concluded that if these theories were right, every possible subjective experience would be contained already in a single firing neuron. Hence these theories are inconsistent.

The analogy with the present argument is obvious. Zuboff’s transformations correspond to the basis transformations in QM. Then it turns out there is a basis in which the state appears trivial, i.e. structureless. Therefore, the state is trivial and cannot explain (or is in contradiction with) the complicated patterns seen in the universe / in subjective experience.

It is instructive to see how Hofstadter and Dennett try to refute Zuboff’s argument (they are proponents of these theories he has taken ad absurdum): They argue, if Zuboff’s argument were right, one could also say that the entire information contained in all the books of the world are already contained in printing each letter from A to Z one single time.

But here is exactly the difference I have discussed in the context of QM: The books in the libraries are read by external observers. These observers read the books according to a specific basis: They read every line from left to right, each page from top to bottom etc. The books contain their information with respect to that “basis”, and therefore printing each letter a single time is insufficient, because the corresponding “basis transformation” is not allowed. The flickering of the neurons, on the other hand, should lead to subjective experience per se, without the help of an external observer, and therefore without a preferred “basis”. Therefore, Zuboff is right, and Dennett and Hofstadter are wrong.

6.3 Is the world a mathematical structure?

Tegmark has argued convincingly that science reduces the world to a mathematical structure [23, 24, 25]. I.e., the picture of the world that is created by science is a mathematical structure. In particular, in science it doesn’t make sense to make a distinction between the structure and entities described by the structure, because there is nothing that science could say about such entities except for what is already contained in the structure.

Tegmark’s view is clearly that this picture created by science is complete, i.e. the mathematical structure can stand on its own ground and is the world (or the multiverse) in which we live and are a part of.

This view is challenged by the argument I have given here. If we take QM in the EI, the mathematical structure is the state vector and its time evolution. This structure has actually turned out to be empty if it stands on its own. It becomes a nontrivial structure only in relation to an external observer, or through the interaction with an environment which is not part of the state vector already.

PWT doesn’t seem to have this problem at first glance. The structure is now given by the state vector and the particle trajectories. But if we take the mathematical universe
serious, on a fundamental level we shouldn’t even speak of particles as entities separate from the mathematical structure. There are only the trajectories, and it is a pure language convention to assign them to entities called particles. So, the trajectories form a set of $3n$ real-valued functions of time (where $n$ is the number of particles). What kinds of transformations should we allow on the $3n$ functions and claim that these transformations don’t change the structure, or don’t change the “information” contained in the structure? Why should we consider the $3n$ functions as trajectories of $n$ particles in 3 dimensions and not, say, of 3 particles in $n$ dimensions? I.e. how is our observation of a 3-dimensional space filled with objects reflected in the “structure” of trajectories? It seems to me that we run into problems similar to the EI, and that the following statement is fundamental:

A structure is a structure only with respect to some observer or environment outside the structure who reads off the structure as a structure in a specific way.

This statement requires further discussion and justification. At the moment one can say that the only interpretation of QM which has this statement built in is the CI.

### 6.4 Schrödinger’s Problem

In [26], Schrödinger writes:

“The thing that bewilders us is the curious double role that the conscious mind acquires. On the one hand it is the stage, and the only stage on which this whole world-process takes place, or the vessel or container that contains it all and outside which there is nothing. On the other hand we gather the impression, maybe the deceptive impression, that within this world-bustle the conscious mind is tied up with certain very particular organs (brains), which [...] serve after all only to maintain the lives of their owners, and it is only to this that they owe their having been elaborated in the process of speciation by natural selection.”

Schrödinger compares the situation with an artist who places a picture of himself as an inconsiderable minor character in one of his paintings. This seems to him the best allegory for the confusing double role of mind. On the one hand it is the artist who created everything; in the completed work, however, it is only an unimportant decoration which could have been left out without changing the total impression substantially.

The text is part of Schrödinger’s philosophical work, at that time totally unrelated to QM. But now we see that the situation in QM is similar, if we replace “mind” by “measurement”: In the CI, the measurement is central. It is the only stage on which the whole physics-bustle takes place, and the state vector is justified only as a model to predict the statistics of measurement results, with no independent existence. In the EI, the measurement process is just a little interaction process like many others, and is completely included in the picture of the state vector, as a “minor character” that could be missing without changing the picture substantially. This is the strange double role of
the measurement.

It seems that one of these views alone cannot survive. If the CI is taken alone, one may respond: “But why should we mystify the measurement? I can model the measurement inside QM, as a part of the unitary evolution of the state vector, without giving it such a fundamental role.” If, on the other hand, the EI is taken alone, we have seen that the resulting picture is not a picture anymore. It is an empty nothing. Only together, as complementary views on QM, the CI and EI make sense.

The strange double role of the measurement, just as the strange double role of the mind, is a problem most fundamentally related to what we do when we do science. We create a picture of objects; a picture created by subjects. The double role is fundamentally built into science. I conjecture it cannot be resolved within science.

References

[1] H. Everett, “Relative State Formulation of quantum mechanics”, Rev. Mod. Phys 29, 454 (1957)

[2] B. De Witt and N. Graham (eds.), “The Many- Worlds Interpretation of Quantum Mechanics”, Princeton Univ. Press (1973)

[3] D. Deutsch, “Quantum Theory as a Universal Physical Theory”, Int. Journal of Theoretical Physics 24, 1 (1985)

[4] E. Joos and H.D. Zeh, “The emergence of classical properties through interaction with the environment”, Z. Phys. B 59, 223 (1985)

[5] W.H. Zurek, “Decoherence and the Transition from Quantum to Classical”, Physics Today 44, 36 (1991)

[6] E. Joos et al. “Decoherence and the Appearance of a Classical World in Quantum Theory”, Springer (2003)

[7] M. Dugic, J. Jeknic-Dugic, “Which Multiverse?”, arXiv:1004.0148 [quant-ph] (2010)

[8] J. Jeknic-Dugic, M. Dugic, A. Francom, “Quantum Structures of a Model-Universe: Questioning the Everett Interpretation of Quantum Mechanics”, arXiv:1109.6424 [quant-ph] (2011)

[9] D. Wallace, “Worlds in the Everett Interpretation” Studies in the History and Philosophy of Modern Physics 33, 637 (2002)

[10] S. Foster und H. Brown, “On a recent attempt to define the interpretation basis in the many worlds interpretation of quantum mechanics”, Int. Journal of Theoretical Physics 27, 1507 (1988)
[11] M. Dugic and J. Jeknic, “What is ‘system’: Some decoherence theory arguments”, Int. Journal of Theoretical Physics 45, 2215 (2006)

[12] G. Ghirardi, C. A. Rimini, and T. Weber, “Unified dynamics for microscopic and macroscopic systems”, PRD 34, 470 (1986)

[13] H.D. Zeh, “On the interpretation of measurements in quantum theory”, Found.Phys. 1, 69 (1970)

[14] D. N. Page, “Sensible quantum mechanics: are probabilities only in the mind?”, Int.J.Mod.Phys. D5, 583 (1996)

[15] E.P. Wigner, “Symmetries and Reflections”, Indiana University Press (1967)

[16] H.P. Stapp, “Mind, Matter, and Quantum Mechanics”, Springer Berlin (1993)

[17] D. Bohm, “A Suggested Interpretation of the Quantum Theory in Terms of ‘Hidden Variables’”, Phys.Rev. 85, 166 (1952)

[18] P.R. Holland, “The Quantum Theory of Motion: An Account of the de Broglie-Bohm Causal Interpretation of Quantum Mechanics”, Cambridge University Press (1993)

[19] H.R. Brown and D. Wallace, “Solving the measurement problem: de Broglie-Bohm loses out to Everett”, Foundations of Physics 35, 517 (2005)

[20] C. Wetterich, “Emergence of quantum mechanics from classical statistics”,\n\texttt{arXiv:0811.0927 [quant-ph]} (2008)

[21] M.F. Pusey, J. Barrett, T. Rudolph, “On the reality of the quantum state”, Nature Phys. 8, 476 (2012)

[22] A. Zuboff, "Story of a Brain", in D. Dennett and D. Hofstadter, “The Mind’s I: Fantasies and Reflections on Self and Soul” (Basic Books, 1981)

[23] M. Tegmark, “Is ‘the theory of everything’ merely the ultimate ensemble theory?”, Annals of Physics 270, 1 (1998)

[24] M. Tegmark, “Parallel Universes”, in \textit{Science and Ultimate Reality}, J.D. Barrow, P.C.W. Ellis, C.L. Harper (eds.), Cambridge Univ. Press (2004)

[25] M. Tegmark, ”The Mathematical Universe”, Foundations of Physics 38, 101150 (2008).

[26] E. Schrödinger, “Mind and Matter”, Cambridge Univ. Press (1958)