MODERN PHYSICS, DETERMINISM AND FREE-WILL

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ABSTRACT: Here is analyzed a notion of free-will based on deterministic physical laws, where the freedom comes from delayed refinement of the initial conditions, assumed to be incompletely specified. It is argued that if this hypothesis poses some problems, the same problems appear in the case of free-will based on indeterminist physical laws. Arguments from relativistic cosmology and quantum mechanics are presented, supporting the idea that the initial conditions are not completely specified from the beginning, and they need to be partially delayed, and subsequently refined. This kind of delayed initial conditions mechanism is shown to provide an interpretation of quantum mechanics which offers an alternative to the discontinuous collapse of the wave function, solving by this some problems due to the presumed discontinuity in the unitary evolution. An imaginary experiment meant to establish the existence of free-will is proposed and discussed.

KEYWORDS: Determinism, free-will, interpretation of quantum mechanics, initial conditions, quantum states, Hilbert space, orthonormal basis.

1. Determinism in physics

1.1. Freedom versus laws in the physical universe

From the beginning of their existence, humans were fascinated, or at least interested for practical reasons, in the regularities observed in the universe. This preoccupation evolved, eventually leading to the natural sciences. Physics managed to explain a virtually infinite range of phenomena in terms of a small number of fundamental principles. To describe a physical process, one needs to describe how a system changes in time. The quantitative descriptions of this change are given by evolution equations. The evolution equations involve the

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physical quantities and some of their partial derivatives – they are partial differential equations (PDE). They have the nice property that, by knowing the initial conditions – i.e. the values of all the quantities involved at a time t_0, including some of their partial derivatives– then the values of all the quantities at another time t are uniquely determined. That is how determinism appears in physics.

We define the state of a system at a given time t_0 to be the collection of all the physical quantities involved (such as the positions of the particles, the values of the fields, etc.), and all of their partial derivatives required to construct a complete set of initial data. We call the set of all possible states, the state space. A state space and its evolution equations form a dynamical system.

One central purpose of physics is to find the laws which describe all the physical phenomena. We would like this description to be as complete as possible. And what can be more complete, than knowing that there exists a solution which is unique? For this reason, the deterministic laws are considered an ideal in physics. Even the statistical branches of physics are reducible to deterministic laws.

While this ideal was very appreciated in physics until the beginning of the XXth century, it made many thinkers worry that this is the end of the free-will. If the universe is governed by laws which dictate everything, there is no room for freedom. If the universe is deterministic, then we, humans, are nothing but blind matter, changing by rules which we can't control.

1.2. An out of time view

Each state is thought as a point in an abstract geometrical space conceived as a representation of the state space. If we choose an initial state, a deterministic evolution equation determines a chain of successive states. This is a curve in the state space (see Figure 1). If the evolution is not deterministic, we would expect that there are more curves passing through a given point in the state space, and that they branch whenever randomness occur (*cf.* Figure 2).

This out of time view based on the state space is often named „God's view" or „bird's view", and it applies to all physical laws we know so far. It is difficult to imagine physical laws which cannot be described in this way. The things became even more „a-temporal", when the theory of relativity entered the scene. This theory dethroned not only the absolute space and time, but even the absolute simultaneity. It appeared to show that time is very much like space, and that we actually live in a frozen four-dimensional block universe.

On the other hand, it is difficult to ignore our inner experience, which seems to have no doubt that there is something more than this collection of configurations represented by the states from the state space. A „reductive block universe" would claim that there is no problem including the description of our feelings in the state space. The supporter of reductionism would argue that even the feelings that we have when reading a poem or listening to music, thinking at God or being in love, all of them, are nothing more than states of our brain. States which can, at least in principle, be observed and recorded by sufficiently advanced technologies. Apparently, even „my thinking that I am" is just a configuration of a system made of atoms.

It is always possible to show that this view is reductionism, and in fact there are emergent phenomena which we should consider. It is true, but what is important from the viewpoint of the supporter of reductionism viewpoint is not that the emergent phenomena can be explained in terms of configurations of the matter, but that, in principle, they correspond to matter configurations, and they can be fully recorded as such configurations.

I don't wish to enter into this kind of debate. It is undeniable that science made spectacular progresses, but there are fundamental questions which are still unanswered. I will focus only on the physical and mathematical part of the problem, and see how can it be compatible with something beyond it (something whose nature and existence we will not here speculate about).

1.3. Quantum indeterminism

With the advent of quantum mechanics, the hope that, despite the rigidity of physical laws, we can still be free, came back to life. Quantum mechanics seemed to have an irreducible, built-in indeterminism. But, as we know, the deterministic laws seem to be more complete than the indeterminist ones. This made even some of the founders of quantum mechanics, like de Broglie, Schrödinger, Einstein (de Broglie, 1927; Einstein, Podolsky, and Rosen, 1935; Bohm, 1951) search for more complete laws, or at least prove the incompleteness of quantum mechanics. To complete the laws of quantum mechanics, de Broglie, Vigier, Bohm and others tried to add new quantities, which had to be unobservable, being therefore called hidden variables. These efforts were severely ruined by evidence that nature violates Bell's inequalities (Bell, 1964, 1966; Clauser and Shimony, 1978; Aspect et al., 1982a, b; Aspect, 1999). The only possible workarounds remained the non-local theories of hidden variables of

Bohm (Bohm, 1952; Bohm and Hiley, 1993; Bohm, 1995) and others derived from them. These approaches are presently still very artificial, rely on faster-than-light communication, and cannot be tested experimentally, because they just try to mimic the quantum mechanics' predictions.

The principles of quantum mechanics are foundational at the deepest level, therefore they should apply to everything physically standing out. This is why the most spread opinion is that the universe is fundamentally indeterminist.

We shall see later in this article that one of the postulates of quantum mechanics, the projection postulate, contains assumptions which create a great difficulty to the theory. We shall see that this assumption can be safely removed, solving by this the difficulty it created. This leads to a simplification of quantum mechanics, which happen to be deterministic. This approach is not based on hidden variables –it does not add extra quantities, it relies solely on the wave function and the data contained in it. Moreover, this approach provides an explanation, or an interpretation, of quantum mechanics.

1.4. Freedom from indeterminism?

It is easy to see that, even if the universe would be indeterminist, this would not guarantee the existence of free-will.

Indeterminism brings a random element in the evolution equations. It is like, from time to time, the system throws a die to see what it should do next. If humans base their choices on random inputs, then this by itself doesn't make them free. Therefore, indeterminism is not a sufficient condition for the free-will, for the same reason why dice don't have free-will.

The problem of free-will is made even more difficult by the fact that probably most, and possibly all, of our actions are determined by biological and psychological laws. How can we distinguish among so many contradictory tendencies, compulsions, desires, fears, which usually influence our behaviour, and how can we isolate from them our real will? How free is our will, if it is overwhelmed by so many factors which already preprogrammed us? This is an important problem, which will not be discussed here.

1.5. The interface problem

There is an important problem concerning the relation between indeterminism and freedom. Let's consider an indeterminist universe. We will assume that in general the universe evolves according to deterministic laws, and from time to time there are indeterminist jumps – as in the case of quantum mechanics, where the unitary evolution governed by Schrödinger's equation is interrupted from time to time by the wave function collapse. Assuming that an agent uses this randomness to perform free choices, she must act precisely at the appropriate moment and position where the branching appears. We can consider the universe as a controlled dynamical system, in which the control is made by the mean of an interface –a „switch" which allows the choice of one branch among more. The agent cannot act by the physical laws of the universe to make the choice, because this kind of choice would contradict the randomness. She has to act from outside the causal flow of the universe (whatever „outside" means), but her influence has to affect the physical universe at the precise moment and positions where the branching would happen. We will name this the interface problem:

What are the precise moment and positions in which the agent manifests her influence in choosing among the possible branches, and how does she act upon the universe to materialize her choice?

Here lies one big problem, unnoticed by the proponents of free-will based on indeterminism. To actually be free, the agent needs to be able to choose so that the effects of the choice are those intended. The effects are not manifest in the configuration immediately following the branching. The configuration after the branching has to evolve, so that the agent can see where it is going – what effects does it entail. Excluding the possibility that the agent computes instantaneously the consequences of the possible choices, or that she is a clairvoyant, the choice has to be done not at the branching time, but later, when the consequences are at least in part visible. Otherwise, we cannot talk about free-will, it is more like blind chance. But if the agent makes her choice at a time *tchoice* later than the moment *tbranching* it follows that the choice is delayed, but it applies retroactively until the moment of the branching (*cf.* Figure 3). This raises the following question:

> *If, to account for the consequences, the choice has to be done after, and not at the branching moment, and if it applies "retroactively" to the branching moment, then why wouldn't be possible that the branching moment can be even at the beginning of the universe?*

The difficulty of the interface problem is increased by the fact that the choice must be non-local. To see why, let's recall

Einstein-Podolsky-Rosen experiment (Einstein, Podolsky, and Rosen, 1935), in Bohm's version (Bohm, 1951). If the agent (say Alice) has one of the electrons, and Bob has the other one, and if they decide to measure the spin along the same direction, then the two spins have to add up to 0. Viewed in the state space, there is a branching at Alice's electron (corresponding to the spin $|\uparrow\rangle$, respectively $|\downarrow\rangle$), and another one at Bob's (corresponding to opposite spins). The two branching have to be correlated, so that the spins add to 0. If Alice's free choice at one point is based on the spin uncertainty of her electron, then her choice automatically has to apply to Bob's electron too[2]. But since Bob and Alice can be separated by a space-like interval, we conclude that if she bases one of her free choices on her electron, she has to affect Bob's electron in a non-local manner.

This observation may not look so distinctive, because we already knew that quantum mechanics has non-local essential features. But it has an interesting consequence. Since the two electrons interacted in the past, and then they separated (remaining entangled), the choice made by Alice can be viewed as extending into the past, at least until the moment when the two electrons were together. We can amplify this argument by using Wheeler's delayed choice experiment (Wheeler, 1977, 1978, 1983), and make her choice extend millions of years into the past. What if her choice can actually affect the initial conditions of the universe? If we accept that her free-will relies on the quantum randomness in such a non-local and retroactive way, why shouldn't it rely on the branching which occurs at the very beginning of the universe?

From the above arguments, it is easy to see that a deterministic universe would offer the same fertile ground for the free-will, as an indeterminist one. The difference is that, instead of choices based on randomness which appears from time to time, the agent chooses based on the only randomness which can exist in a deterministic universe – that of the initial conditions.

1.6. Freedom from determinism?

We saw that indeterminism by itself is not enough to guarantee the free-will. But is indeterminism, at least, a necessary condition for the free-will? In other words, if the universe is deterministic,

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[2] A word of caution: when I say „Alice's choice", I do not refer to the choice of the direction along which to measure the spin. I am referring to the choice of the outcome of the measurement, in the hypothesis that her free-will relies on quantum randomness.

does this necessarily entail that there is no free-will? This question was partially answered by section 1.5.

Determinism does not necessarily forbid free-will, for the following reason. If there are evolution equations to which all of us obey, we cannot have the freedom to break them, in order to make choices which influence the state in which the universe will be later. But the state of the universe at a later moment is not determined only by the laws, but also by the initial conditions. If, by any chance, we would have the possibility to make choices concerning the initial conditions, then this would be compatible with the free-will (Hoefer, 2002; Stoica, 2008a, b, c). This is represented in Figure 4.

But wouldn't this kind of choice of the initial conditions violate causality? It would not, because we don't change the initial conditions which were already fixed. We consider that the initial conditions were fixed only partially, and we add constraints which refine them, but which are compatible with them. This way, there is always a non-empty set of solutions to the PDEs describing the system (being it the entire universe).

Instead of considering the evolution of the state of the universe as a definite path in the state space, we can consider it a set of constraints, of propositions about the state space. These propositions respect the following rule: to be logically consistent with all the propositions from its past. This shows that there is no violation of causality, and in the same time that the path in the state space is not completely defined, but only refined in time, by each new proposition imposing constraints on the system.

The analysis made in section 1.5 actually shows that similar problems concerning locality and causality has a notion of free-will based on indeterminism. The only difference is that this counterintuitive feature is not so obvious in the indeterminism-based free-will, as it is in the determinism-based one.

This compatibility between determinism and free-will is not the standard compatibilist position. We do not define a „weaker" notion of free-will, to make it compatible with determinism.

In fact, in this article there will be given no precisely definition of what free-will is. Only what it is not: free-will cannot exist when the behaviour of the agent is completely determined by the past, with or without random inputs. There is much to be said about determinism, but here we are only concerned with the problem of the compatibility between the free-will and the physical laws, especially the deterministic laws.

2. Initial singularity and delayed initial conditions

The Big-Bang model proved to be very successful in explaining the cosmological observations. General relativity is a theory whose predictions were confirmed to an astonishing degree, passing all the experiments devised to test it. By general relativity, when applied to the cosmological observations, it follows from the singularity theorems (Penrose, 1965; Hawking, 1967; Hawking and Penrose, 1970; Hawking and Ellis, 1995) that there was a singularity at the beginning of the universe.

At a singularity, the quantities involved in the field equations become infinite. These quantities are the space-time curvature and the energy-momentum tensor. If we want to write the initial conditions of the universe, the equations will be undetermined, having the form

$$\infty = \infty$$

This means that it makes no sense to discuss about the initial conditions at the initial singularity (*cf.* Figure 5). But the notion of initial conditions doesn't necessarily apply exclusively to the initial moment of time. They would make sense even if the universe would have infinite age. The moment at which we define the initial conditions can be freely chosen, because the initial conditions just fix the free parameters of the solution. Therefore, it makes sense to speak about the initial conditions of the universe, specified at a subsequent time t_1 later than t_0.

It seems that relativistic cosmology suggests that the initial conditions should be specified with a delay[3].

2.1. Quantum determinism and freedom

Quantum states and observations.

The state of a quantum system is represented by a vector $|\psi\rangle$ from a vector space (usually named the Hilbert space), which is the state space – in a mathematical description of quantum mechanics. The evolution of the quantum system, that is the modification of $|\psi\rangle$

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[3] This argument relies on the fact that the metric, hence the fields, become singular at the initial moment of the universe. But I should mention an alternative possibility: that Einstein's equations can be replaced by other equations, which are equivalent with them, but which are finite even at a class of singularities named semi-regular (Stoica, 2011a, b, c). This leads to the possibility that the Big-Bang singularity is semi-regular (Stoica, 2011b), and we can therefore write the initial conditions in the equivalent but non-singular formulation of the general relativity.

described by a parameter *t* (called *time*), is described by Schrödinger's equation, which is deterministic and reversible:

$$i\hbar \frac{d}{dt}|\psi\rangle = H(t)|\psi\rangle$$

The solutions, infinite in number, form a space S(H). For any initial state $|\psi_0\rangle$ at an initial moment t_0, there is a unique solution $|\psi(t)\rangle$ (Figure 6). By solving the Schrödinger equation, we obtain a solution of the form

$$|\psi(t)\rangle = U(t,t_0)|\psi(t_0)\rangle$$

where $U(t,t_0)$ is a unitary operator (Figure 6). In the case of *H* independent of time, the unitary operator has the form:

$$U(t,t_0) = \exp\left(-i\frac{t-t_0}{\hbar}H\right)$$

For this reason, the time development of the quantum system is called unitary evolution.

The exact solution of a deterministic equation can be, ideally, determined by measurements or observations. By the measurements at a time *t* we find the state at that time, and from this one, by applying the unitary evolution operator, the state at other moments of time.

The problem is that there is no observation which applies to the full state space. Each property we can observe, is defined for only a part of the state space. Each property is represented by a Hermitian operator, named observable. Any possible outcome of an observation is an eigenvalue of the observable, and the system is found in a corresponding eigenstate of that eigenvalue. The set of all possible eigenstate of the observable is just a small subset of the entire state space.

It follows, from the fact that the system was found to be in an eigenstate of the observable, and from the unitary evolution, that the system had to be in a very special state from the very beginning, so that it evolved in the state we observed (Figure 7) (Weiszäcker, 1931; Wheeler, 1977, 1978, 1983).

2.2. The internal tension of quantum mechanics

There is another problem with this picture of quantum mechanics: for each state there are properties which are not defined for that state. A state which is not an eigen-state of the observable O0, can't have the property corresponding to that observable. For example, position is defined only if the wave function is concentrated in one point, and the momentum is defined only if the wave function is a pure plane wave. This problem becomes manifest when we make two incompatible observations of the same system (Figure 8).

If the two observables do not commute (as operators acting on the state space), they impose incompatible conditions on the system. This seems to imply that the system makes a discontinuous jump (a projection) from one state to another, to accommodate itself with the new observation.

What is known as a fact is that the second observation indeed finds the system in one of the eigen-states of the observable. We also know that the probability is given by the squared cosine of the jumping angle (recall that the state is a vector in the state space, so we can speak about the angle between the states before and after the jump). This is called the Born rule.

This discontinuous jump violates the unitary evolution, and it is the reason why quantum mechanics is considered an indeterminist theory.

The discontinuous jump raises some other problems (Stoica, 2008a):

- It has never been directly observed.
- There is no known explicit process leading to the discontinuity. In fact, all interactions we know fit well in the Hamiltonian description, and the measurement devices are made of systems which obey it. So, where does the discontinuity come from?
- It would violate the conservation laws. In quantum mechanics, the conservation of a quantity is described by the fact that the Hermitian operator associated to that quantity commutes with the Hamiltonian H. Since the evolution is not unitary during the jump, the conservation laws should not hold. Yet, it is known that the conservation laws are not violated, so it follows that the evolution should remain unitary all the time.
- The entanglement is due to the unitary evolution. After two initially separate systems interact, they remain entangled. The outcome of an observation performed on one of the systems should be correlated with the outcome of an observation performed on the other system (Einstein, Podolsky, and Rosen, 1935; Schrödinger, 1935; Bohm, 1951). If the discontinuity is true, then it should explain why the projection of one of the systems is correlated with the projection of the other system.
- The unitary evolution leads to this naturally, but the discontinuous projection by itself would break it, unless we complete it with a mechanism which ensures the correlation.

- A discontinuous jump would depend on the reference frame (see e.g. Aharonov and Tollaksen (2007)).

We shall see that the assumption usually contained in the projection postulate, that the system undergoes a discontinuous projection or collapse, is not necessarily true. The system can undergo the collapse, without necessarily be discontinuous and non-unitary. To show this, I do not add new principles, I just remove from the projection postulate an unproven assumption which adds internal tension to the theory and the inherent complications (Stoica, 2008a).

2.3. Unitary quantum mechanics (quantum mechanics without discontinuities)

I will present here shortly an interpretation presented in more detail elsewhere (Stoica, 2008a, c, 2009).

A quantum observation is usually supposed to leave the system in the same state in which it was prior to the observation. This ideal is reached when the system was already in an eigen-state of the observable. If two consecutive observations are made to the same system, on the properties O_0 and O_1, and if the two observables don't have the same sets of eigen-states, the state of the system is changed. We expect that in the system obtained by composing the measurement devices and the observed system the unitary evolution remains valid, and the conservation laws for that matter. This entails that there is an interaction between the observed system and the measurement devices with which it interacts. This is usually represented as another Hamiltonian interaction, which is added to the Hamiltonian which normally guides the evolution of the observed system.

Could it be possible that the interaction H_0 of the system $|\psi\rangle$ with the measurement device corresponding to O_0, represented by the state vector $|\eta\rangle$, left the observed system precisely in the state which evolved unitarily into the eigen-state of O_1 which was observed later (Figure 9) (Stoica, 2008a)?

This could happen in principle, but wouldn't it be a huge coincidence? Well, it is a huge coincidence, of 0 probability to happen, if we consider that the initial conditions of the measurement device were by chance like this. But if we admit that the initial conditions can be delayed until new constraints are added to them (by the second observation), then this no longer looks like a coincidence. In fact, it is nothing more than what happened in section 3.1, illustrated in Figure 7. Let $|\eta\rangle$ represent the measurement device observing the property O_0 on $|\psi\rangle$. Then, the two systems became inseparable. This means that the combined system is now described as a superposition (linear combination) of states of the form $|\eta\rangle|\psi\rangle$:

$$\alpha_i|\psi^i\rangle|\eta^i\rangle$$

where the α_i are numbers. The above combined state is expressed by means of other states which collectively describe any other state, that which is called an *orthonormal basis* $|\psi^i\rangle$ of the state space of the observed system[4]. We are free to take this basis as being made at t_1 of eigenvectors $|\psi_1^i\rangle$ of the observable O_1, so that $|\psi^i(t_0)\rangle=|\psi_1^i\rangle$. We can take as bases at other moments of time t those obtained from this one by the unitary evolution operator:

$$|\psi_0^i\rangle=U^{-1}(t,t_0)|\psi_1^i\rangle.$$

The state of the total system $|\psi\rangle|\eta\rangle$ becomes $\alpha_i|\psi_0^i\rangle|\eta_0^i\rangle$ at t_0, and $\alpha_i|\psi_1^i\rangle|\eta_1^i\rangle$ at t_1.

The second observation finds the system in one of its eigen-states $|\psi_1^j\rangle$, and from this it follows that the first measurement device is in the corresponding state $|\eta_1^j\rangle$. This means that $\alpha_i=1$, and the other coefficients $\alpha_i=0$, for $i\neq j$. In other words, after the second measurement it turned out that the two systems were in fact separated all the time, and had the precise states which could have lead to the outcome $|\psi_1^j\rangle$ In Figure 10 it is considered that $j=3$. By this, the second observation did not, in fact, add constraints to the system $|\psi\rangle$, which were inconsistent with its previously known state $|\psi_0\rangle$. What the second observation did was to refine the initial conditions of the large system, with a delay.

Let us note that even though the states $|\psi_0^j\rangle$ were obtained by a unitary operator from the orthonormal states $|\psi_1^j\rangle$, they are not necessarily orthonormal, and may even become dependent. In fact, in our case they all become at t_0 equal to $|\psi_0\rangle$ (Figure 10). The operator U is a unitary operator on the total space of $|\psi\rangle|\eta\rangle$, but not on the space of $|\psi\rangle$.

This shows that it is possible for $|\psi\rangle$ to satisfy the constraints of both observations, and still have unitary evolution, without

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[4] The existence of such a special collection of states in a Hilbert space is beyond doubt by two reasons: an effectively listed collection of such states (Fourier pure periodical movements, called harmonics), and – independently – by the *axiom of choice* (or its logically equivalent Zorn's lemma) of the axiomatic *set theory*. The *axiom of choice*: (from any collection we may choose – even in not an effective manner – an element of that collection) is actually an ontologic principle.

discontinuous projection. The projection is smooth, taking place in our example from Figure 10, in the time interval $[t_0, t_0+\varepsilon]$.

We already knew that quantum mechanics seems to ask that the initial conditions are specified with a delay (Weiszäcker, 1931; Wheeler, 1977, 1978, 1983). This means that any new observation refines the constraints, and by this the state of the universe becomes more and more determined. What we learned new from the above explanations is that this very mechanism can be used to explain the appearance of the wave function collapse, in a manner which doesn't need discontinuous jumps. *I will call the interpretation presented here the unitary interpretation of quantum mechanics*, UIQM.

From the viewpoint of this presentation:

- quantum mechanics can very well be deterministic,
- and the appearance of its probabilistic nature is due to the incomplete determination of its initial conditions, not to a presumed indeterminism of its evolution equation.

2.4. Comparison with other interpretations

It is a controversial subject not only which interpretation of quantum mechanics is the correct one, but also whether it needs an interpretation at all. In fact, almost any interpretation adds a different angle, which emphasizes or explains one feature or another of quantum mechanics in terms of more intuitive concepts. The reason why there is no unanimously accepted interpretation is that we cannot test directly the extra assumptions each new description adds, and that none of them can be avoided being based on strange hypotheses, conflicting with our intuitions – previously formulated through senses or/and reason – on time, local interactions, the independence of reality on the observer, etc. From this viewpoint, the interpretation I propose reduces some of the problems of quantum mechanics to the idea that

> *we can delay the choice of the initial conditions, to make them compatible with the future observations, without violating the unitary evolution.*

Since this is, in my opinion, the central mystery of quantum mechanics, we expect it to be present in one form or another in the other interpretations. I agree with most of them, at least partially, and I acknowledge the importance of providing more complementary grounds for the intuition, in a realm in which the intuition seems to fail. By this brief comparative analysis I hope to point the main similarities and differences, but I apologize in advance for any possible injustice done by trying to contain each of these interpretation – on which many profound pages were written – in a small paragraph.

The instrumentalist interpretation of quantum mechanics is concerned only with the possible outcomes of the measurements, and the corresponding probabilities (von Neumann, 1955). For this reason, it is not concerned with the nature of the wave function – it views it as a tool for calculating the probabilities. A similar position is held by the standard Copenhagen interpretation.

By contrast, UIQM *considers the wave function obtained by a measurement*[5] *as being the sole reality, and it views it as a field.* From this viewpoint, it is close to Schrödinger's interpretation (Schrödinger, 1952a, b), that the wavefunction has physical reality, and the particle is actually distributed in space. There is a problem with this view – systems composed of more elementary particles have to be represented as wave functions in a higher dimensional spaces. Superposition of such multidimensional waves lead to the entanglement (Schrödinger, 1935), so Schrödinger's view cannot be local, as he desired. But UIQM has these characteristics too.

Although UIQM is deterministic, it should not be confounded with the hidden variables completions of quantum mechanics (Bohm, 1951, 1952; Bohm and Hiley, 1993). The only hidden things in UIQM are some of the initial conditions, but they are only temporarily hidden, since any such unknown degree of freedom can in principle be determined by observations and statistical averages. There is no need to add superluminal mechanisms which communicate the information at a distance.

Since in UIQM the wave function evolves smoothly towards the state in which it will be detected, one may compare it with the objective collapse approach (Ghirardi, Rimini, and Weber, 1986). My approach does not rely on a presumable non-linearity in the evolution of the wave function, but of course this possibility should not be excluded. On the one hand, the unitary quantum mechanics adds the interaction with the preparation device, and this is, if we restrict our reasoning to the state of the observed system only, an infusion of non-unitarity in the evolution. The unitarity, though, is restored at the level of the larger system. On the other hand, in the context of general relativity non-linearity may even be true, because a non-inertial

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[5] which can be done at a later moment.

change of reference also destroys the unitarity. But I find no compelling reason to believe that gravity plays such a decisive role in the measurement problem in quantum mechanics. In addition, the objective collapse should be able to explain how the collapse is correlated for entangled systems, and this puts it, from this viewpoint, in the same square with the hidden variables theory.

One thing it should be added: the interpretation of UIQM presented here is a complete replacement of the projection postulate. At this moment, I don't have a way to derive the Born's rule from uniformly distributed initial conditions. What we can say is that the result of the most recent observation of the system contains the probabilities for the next outcome, and for this reason the same wave function can play both a probabilistic role, and be a real field. After the observation, it turns out that the wave function was already in the obtained state, which became actual, and the previously known state contained, in fact, information about the potential outcomes – including their probabilities.

One can make some connections between the Many Worlds Interpretation (MWI) (Everett, 1957, 1973; de Witt, 1971; de Witt and Graham, 1973; Deutsch, 1985, 1999), and UIQM. There is certainly a common feature between the very notion of relative states and my view, because adding new observations refines, in UIQM, the possible states of the universe. But there is no branching in UIQM, it is just a refinement of the possible states. It is claimed that MWI is based only on the unitary evolution, and that it removes the discontinuous collapse. In fact, in MWI the evolution remains unitary only if we keep all alternative histories in superposition. For the observers habiting each of these universes from the multiverse, the wave-function collapse raises the same problems as the standard interpretation does. We can conceive a version of UIQM which is like a MWI, if we admit that all solutions exist in the multiverse, and the observations help clarifying which one of them is our universe. But this is done without branching.

In UIQM I acknowledge that the observed system is in fact entangled with all systems with which it interacted in the past. This is not analogous to the inclusion of the environment from the decoherence approach (Zeh, 1996; Zurek, 1998, 2002, 2003a, b, 2004). I find hard to believe that the environment is the cause of selecting the eigen-states, because these depend only on the measurement device. Change the measurement device, and leave the rest of the environment unchanged, and the eigen-states change too. I consider that even in the decoherence interpretation, we should consider that when the system decoheres, its entire past, and all of the systems entangled with it decohere. This simple truth is usually lost in the intricacies of considering a very complex environment. Another problem is that, in the situations given as supporting examples for the decoherence interpretation, the environment which induces the decoherence of the observed system is assumed to be already decohered in a state very close to the classical world. This relegates the explanation to that of why most of the universe is already decohered.

The claim of UIQM is that the observations on a system, by providing initial conditions delayed at various times, should be consistent with one another, and with the Schrödinger equation. By this, it makes stronger claims than the consistent histories interpretation (Griffiths, 1984; Omnés, 1988; Gell-Mann and Hartle, 1990a, b; Omnés, 1992, 1994; Isham, 1994), which generalizes Born's rule to more complex sets of conditions. I claim that the quantum system can be completed, so that the evolution of the larger system is precisely unitary. Equivalently, we can complete the Hamiltonian of the system with the interaction Hamiltonians which represent its past interactions – for example with the preparation device. In addition, UIQM provides a physical interpretation of the wave function, not just an instrumentalist algorithm.

The proposed interpretation can be viewed just as a set of initial conditions delayed at various moments of time. I suggested that these conditions come in fact from the requirement that any interaction changing the type of the particle should be integral – that is, it either happens or not, it is not admitted to participate only partially in superpositions (Stoica, 2009). For this reason, it is purely symmetric in time, the asymmetry being in the experimental arrangement. The conditions can be understood from the „bird's view" perspective – they have to be satisfied at the global level of space-time. UIQM doesn't need a mechanism which goes back and forth in time to negotiate (and change) the consistency of the initial conditions, as in the transactional interpretation (Cramer, 1986, 1988).

UIQM achieves the evolution of the system from a state in which it has been observed at t_0 to the state in which it is observed at t_1. It does not need two state vectors, evolving in opposite directions of time, which ensure the correlations between measurements, as in the two-state interpretation (Aharonov et al., 1964, 1988, 1990; Aharonov and Vaidman, 1991; Aharonov et al., 1993; Aharonov and Tollaksen, 2007; Aharonov et al., 2009). The concept of weak measurement, introduced with the two-state interpretation, with the notions of pre-selection and post-selection, provide a very useful way to think about the intermediate states. The proponents of the two-state interpretation made as well interesting observations about the freewill: they see the destiny as the past-directed arrow of time, through which our *free-will* influences the past (Aharonov and Tollaksen, 2007). But I don't see the need of having two time directions and two state vectors evolving in opposite time directions. We can view the two-state interpretation as adding a hidden variable – the second state, which evolves backwards in time. UIQM doesn't require such a hidden variable, since there is already the system which performs the preparation, which is still entangled with the observed particle and comes with its own indetermination of the initial conditions.

Admittedly, there is subjectivity involved in which interpretation to prefer. Probably most quantum physicists have a preferred way of thinking, like we have a language in which we usually think, and they switch if needed to other interpretations, when they consider them more appropriate to the problem at hand. For practical purposes, I consider simpler to use the instrumentalist interpretation. If one wants to have a mathematical and physical representation of what happens behind the scenes, I encourage the usage of UIQM, even if it may require some efforts to think from the „bird's viewpoint". Each interpretation comes with its own trade-off, in that it is based on at least one counterintuitive principle – its „central mystery". This is easy to understand, because quantum mechanics is very counterintuitive. In the case of UIQM, the central mystery is the interplay between unitarity and delayed initial conditions.

3. The convergence hypothesis

3.1. Free-will based on delayed initial conditions.

We have seen that general relativity seems to imply a delay of the initial conditions, since they are undetermined at the time 0 (section 2). Also, we have seen that quantum mechanics is not necessarily indeterminist, and that it also implies that the initial conditions should be delayed (section 3). We have argued that the interface problem suggests that even for indeterminist theories, the free-will is non-local and operates by delayed initial conditions – even though for indeterminism the initial conditions are not necessarily delayed until the beginning of the universe, but only until the most recent branching (section 1.5).

I tried by the above arguments to build the case for a free-will based on delayed refinement of the (incompletely specified) initial conditions. We will discuss further the possibility of testing this kind of free-will (Stoica, 2008b, c). This discussion applies, due to the discussion in section 1.5, also to the free-will based on indeterminism.

3.2. An imaginary experiment

Let's assume that someday, probably in a very distant future, our science and technology will allow us to decipher the detailed processes which take place in the brain. Moreover, let's assume that we will be able to monitor these processes, without disturbing them, to the level of particles.

If this technology is impossible, we can ask Laplace's daemon to help us with this experiment. Then, we will be able to track all the causal chains which lead to the decisions we take. It wil appear, because of this, that everything we do is predetermined by the initial conditions.

How could we verify that the actual connection is actually the reverse – that it is our will which chose, retroactively, among the admissible initial conditions?

To do this, we follow the brain's processes, to the finest detail, while the subject solves various clearly definite tasks. We can view, at the smallest detail, the brain as a non-deterministic automaton. The non-deterministic part comes both from the outside environment, and from the inside (biological, chemical and physical processes, which cannot be determined by our brain activity, but which determine it as we shall consider here). In other words, the non-deterministic part consists in the uncontrolled initial conditions.

By having all this information, we can calculate the probability for a given task to be solved, by considering the non-deterministic input to be purely random; let P_{random} be this probability. Then, we measure the success rate $P_{success}$ in solving the given tasks. By comparing the values P_{random} and $P_{success}$ we can conclude *a measure in which the subject is an agent endowed with free-will*. For example, if the tests are solved more often than it would be statistically normal, then the subject has the capacity to choose among the possible initial conditions those which are more favorable to his or her intentions.

Discussion

The proposed experiment can work as well, with minimal modifications, in the case when the universe is indeterministc. In this case, we need to supplement the initial conditions with the conditions specifying the branching. As a matter of fact, both possibilities would be confronted with the following problems.

How can the agent – supposed to be a subsystem of the universe – select a branching (in the indeterminist case), or a refinement of the initial conditions (in the deterministic case)? This is the interface problem (section 1.5). If this selection is due in the virtue of the physical laws, isn't it in fact determined by the past?

It seems that the only alternative is that the selection is made by an entity from the outside of the universe – an entity which is the real free agent, and who controls the flesh and blood body. This explanation has the big problem that it appeals to something even less understood and less verifiable: by concrete physical tests (verifiability), or by mental experiments (understandability).

It is hard to escape the impression that free-will based on delayed and refined initial conditions would modify the past. If the past consists only in incomplete sets of initial conditions, then there should not be a problem, and no causality violation, to refine these conditions, but I admit that this is counterintuitive. Probably a way to make this picture more intuitive would be to appeal at the „bird's view" (section 1.2).

The interface problem of the free-will based on indeterminism requires a non-local mechanism which ensures the quantum correlations, if the source of randomness is a system which is entangled with another system. It also requires an explicit mechanism of how the free-will intervenes in the evolution equations. These problems are shared by the free-will based on delayed refinements of the initial conditions.

The arguments presented here have tried to show that modern physics not only is compatible, but also supports the determinism, together with the possibility that the initial conditions are not completely established from the beginning, but rather they are incomplete, and subsequent choices and observations refine them. We also tried to show that the problems of this kind of free-will are in fact present in the case of an indeterminist free-will too. We have proposed an experiment which will, in principle but not very soon, show us if one of these two versions of free-will exists.

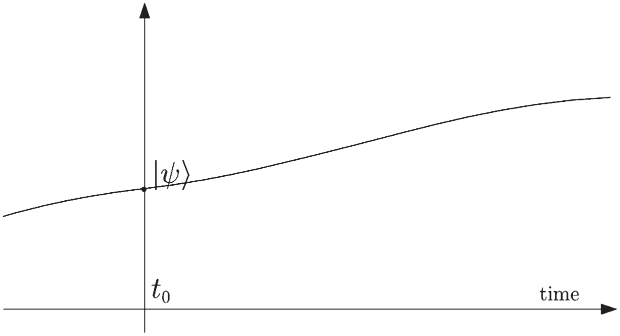

Figure 1 – In a deterministic universe, for given initial conditions at the time t_0, the evolution equations imply a unique state at a future time t_1.

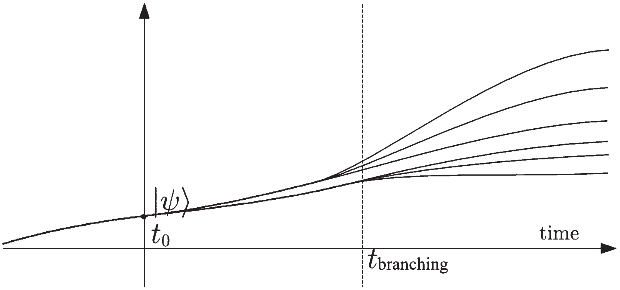

Figure 2 – In an indeterministic universe, the initial conditions may correspond to more possible states at a future time, and there is a branching in the evolution.

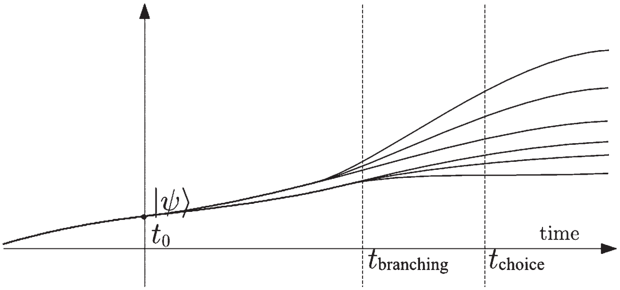

Figure 3 – For the choice to be free, it has to be done not at the branching time $t_{\text{branching}}$, but later, at a time t_{choice}.

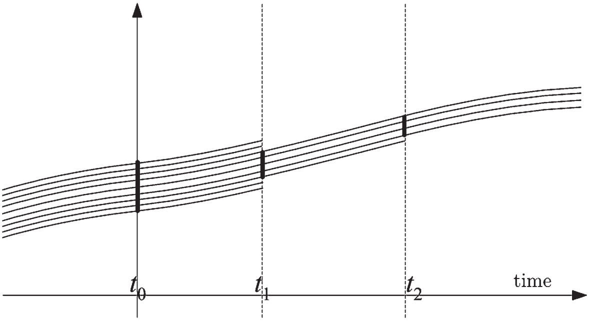

Figure 4 – A deterministic universe can have incompletely determined initial conditions, which can be refined by ulterior choices. By this, determinism and the free-will may be compatible.

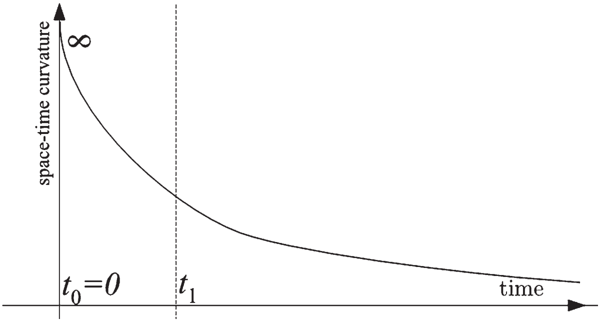

Figure 5 – It makes no sense an initial condition at $t_0=0$, because the involved quantities are infinite. But initial conditions at later times make perfect sense.

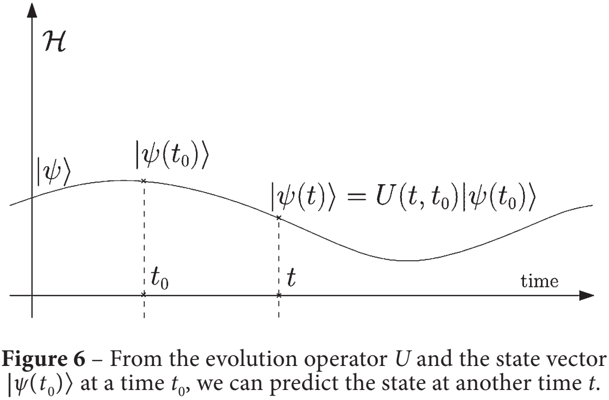

Figure 6 – From the evolution operator *U* and the state vector $|\psi(t_0)\rangle$ at a time t_0, we can predict the state at another time *t*.

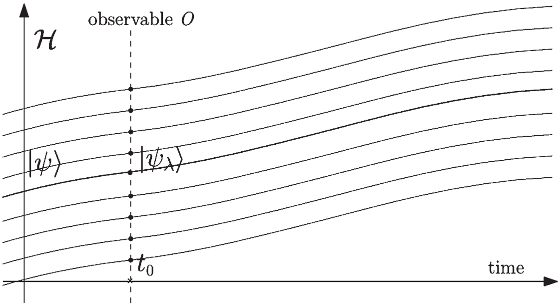

Figure 7 – The quantum system had to be from the beginning in a very special state, precisely one which would have evolved in an eigenstate of the observable at t_0.

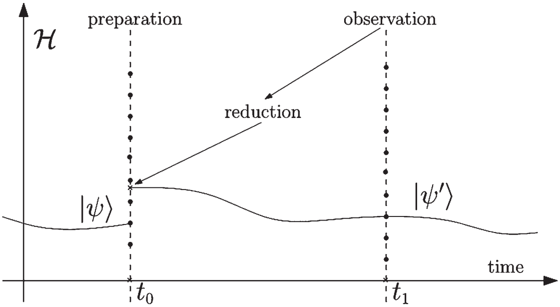

Figure 8 – Two different observations of the same system seem to impose incompatible conditions on the solution. This is the origin of the wavefunction collapse.

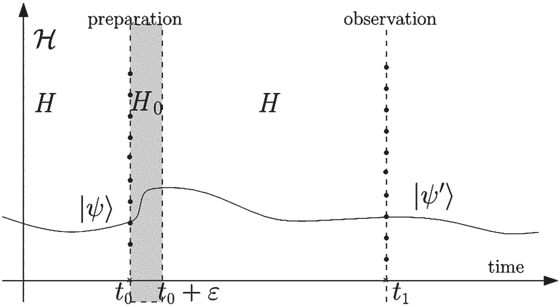

Figure 9 – What if the observation of the property O_0 left the observed system precisely in one of the few states which could evolve into an eigenstate of O_1?

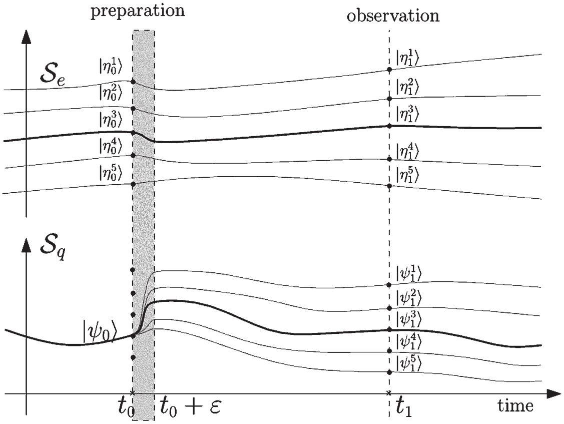

Figure 10 – The second observation decides in which relative states were the observed system $|\psi\rangle$ and the preparation device $|\eta\rangle$.

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