

## Quantum theory appendix 4: Three options for the future on quantum theory

As we described earlier, to apply the method of physics in a box, we have to identify a subsystem of the world and consider it to be isolated from the rest of the universe. Let us take a hydrogen atom as such a system. We then need to define a space of configurations, which consists of all the possible ways the system might be described at a given time. In quantum mechanics this is a space consisting of all the possible quantum states of the system. This can be conceived of as an abstract space with one point for each quantum state that the system might be in. Generally this will be a high dimensional space; in many cases it is even infinite dimensional. But it is simple in one way, which is that any two quantum waves or states can be added, giving another quantum state. This is called the superposition principle. The set of all such quantum states is called the Hilbert space of the system.

Many experts on the foundations of quantum mechanics believe that the Hilbert space is not real, in the sense that there is no objective correspondence between an individual quantum system and a point in Hilbert space. According to some experts, a state or point in Hilbert space corresponds not to one system in nature-but to an ensemble consisting of a very large number of systems, each prepared in the same way. For others, a state in Hilbert space represents our knowledge of the system, in terms from which we can easily deduce the wagers we would bet on the results of any observation we might carry out on the system.

Also necessarily outside the quantum system is the clock by which the changes of the state of the quantum system in time are recorded. The primary equation in quantum mechanics is called the Schroedinger equation. It tells us how the waves-or more generally the quantum states-evolve in time. It plays the same role as Newton's law of motion. But it cannot be seen as describing directly how an individual electron moves. Instead, it tells us how the betting probabilities that we would give to outcomes of different measurements change in time.

Because of this, the Schroedinger equation does not describe directly motion in space. It describes change in time as motion in the Hilbert space of states. Just like Newton's laws give a curve in the space of configurations, Schroedinger's equation gives curves in the abstract Hilbert space.

One way to see that the evolution on the Hilbert space is not real change in time is to notice that it is not always correct. For we can never forget that the quantum state represents a description of a subsystem of the universe. We can impose on that system by choosing to prepare it in a particular initial state. When we do this we have to move the quantum state immediately to the state we have prepared. Otherwise it doesn't represent the system we are experimenting with. No matter that this disrupts the evolution in time given by the Schroedinger equation. That only applies to the system when we are not interfering with it.

We impose on the system again when we make a measurement. When we do, quantum mechanics will usually predict probabilities for different possible outcomes. When we do the actual experiment, we see only one outcome. To correct for quantum theories failure to give a precise description, we just have to set the quantum state to the state associated with the outcome of the measurement we observe.

So there are two rules for how a quantum state evolves in time. When we measure it or prepare it, we have to set the state to that which we prepare or observe. When we don't measure it it evolves according to the Schrodinger equation.

The fact that there are two rules rather than a single rule is called the measurement problem. But it is only a problem if one has the mistaken impression that the quantum state is real. But once we see it as an instrument of our knowledge, it is evident that there should be two ways it can change. A clock on the night table also has two ways of evolving. When it is plugged in and once set, it advances on its own, minute by minute. This is like the evolution of the quantum state under the Schroedinger equation. But from time to time we have to interfere, to set it or reset it, for example after a disruption in power. There are convenient buttons on the side to do that.

But there is in nature just one thing happening. A real theory, that described what is really going on must have just one rule for how systems change in time. One way to phrase the search for a deeper version of quantum physics is that we seek a theory that has only one way that things evolve in time.

At this point we have, roughly speaking, three options.

The first is to presume that the quantum states are approximations to some more complete description of individual systems. That approximation, we may presume, is pretty good for microscopic systems like individual electrons and atoms, but gets worse as the system gets larger. By the time we get to the level of human beings the quantum description is a very bad approximation. So the real physics has states that are approximately described as superpositions of electron states, but no states that are anything like superpositions of states in which human beings believe distinct things or experience distinct levels of affluence.

This is Roger Penrose's view. The reader may learn more about it from his excellent books; for our purposes all we need to know is that it is a coherent view based on an assumption that quantum mechanics is not the right theory, but is only an approximation to the true theory.

The second option is to allow quantum states to apply equally to all systems, small and large, but only with the proviso that quantum states are nothing close to complete descriptions of the reality of individual systems. One version of this kind of theory asserts that quantum states are coded forms of information and belief about subsystems of the world that observers can use to justify betting odds for the outcomes of experiments. Other versions claim that quantum states describe, not individual

systems, but large ensembles of similarly prepared systems. On each of these theories, there is room to postulate the existence of a deeper level of description which might be applicable to individual systems.

The third option is to postulate that quantum states do exactly correspond to the reality of individual systems on all scales. For this to be true, our perceptions of reality must be largely illusions. The real state of the world is some enormous superposition of different possibilities, which corresponds to nothing like our observations or experience of the world.

The advantage, for what its worth, of this third option is it lets us believe the search for the ultimate theory is largely over. It presumes that quantum mechanics is the final form of physical theory, which will never be superseded. The details may change, and we may learn more about the elementary particles and forces, but the framework of describing nature as states in an infinite dimensional Hilbert space need never, and likely can never change.

The disadvantage is this line of thinking must explain why we observe things like positions of large objects, written type, property and levels of wealth to be things that have definite values, when in reality, if the quantum state is real, they are not.

There are attempts to do this, but they do not convince me. One attempt is the many worlds interpretation, proposed by Hugh Everett and championed by Bryce DeWitt, David Deutsch and many others. The basic idea is that anytime the quantum state is a superposition of definite outcomes the universe is said to “split” into different “branches.” In each branch a different of the possible outcomes is realized.

Proponents of the many worlds interpretation believe that the universe does not exist in space or spacetime, but that the universe really is a point in the abstract infinite dimensional Hilbert space. To them the point in Hilbert space is real and everything else is an illusion. Consequently to them, time really is nothing but motion in the infinite dimensional Hilbert space.

I believe that these theorists-smart as many of them are-are making a big mistake. They are confusing a mathematical construction for a radical vision of a real world. Their physics is a branch of mysticism because it leads them to believe that everything we experience is an illusion, a veil which hides what is really real from us.

More particularly, the proponents of the many worlds interpretation of quantum mechanics are taking a mathematical description invented to keep track of measurements made on small subsystems of the universe and proposing that it gives a precise description of the entire universe. This is another instance of the cosmological fallacy. It fails not just because it is implausible, but on its own terms.

The problem is the many worlds interpretation is committed to saying that all the possible histories of the universe are equally real. But this includes histories where

observers see results that contradict the probabilistic predictions of quantum mechanics. This is analogous to the problem that in a finite world some coin tossers will see a long run of heads. However, it is much worse, because there is no meaning in the many worlds interpretation to saying that the observers who see quantum predictions fail are less likely than those whose observers will affirm quantum mechanics. They are all equally likely because they are all equally real.

In their mystical construction of the world, nothing has a definite property, because the sum of any two realities can be another reality. Moreover every single reality can be expressed as a sum of two other realities-and in an infinite number of ways. I may be accused of putting this too strongly, but I am not. If a quantum state is a summary of our information about betting probabilities, then the fact that two quantum states can be added to make another is a statement about how probabilities we might bet may be combined. If the quantum state is real, then the superposition principle is exactly the statement that any reality can be decomposed into a sum of two realities. So if an electron may be here in one reality and there in another, there are an infinite number of possible realities where it is some here and some there.

This is also a mythical construction of a world in which time no longer exists. To see why, let me recall that any application of doing physics in a box is necessarily an approximate description of part of the world. If quantum mechanics really gives the complete description of an individual system, it must be expandable to a description of the whole universe. There are certainly lots of attempts to construct and play with models of universes in the quantum formalism-this subject is called quantum cosmology. Can this really be made sense of, or is the application of the quantum formalism to the whole universe an aspect of what we have called the cosmological fallacy?

The first step in extending the quantum state to the whole universe is to include we the observers in it, together with our measuring instruments and clocks. This is a move that has the most dire consequences for our notion of reality, if we take as axiomatic that the quantum state represents reality. To illustrate this let us consider a qbit-a quantum bit of information which has two settings, NO and YES. If it reads YES we won the lottery. If it reads NO we didn't. We can model ourselves as quantum systems interacting with the qbit, say by opening a qmail from the lottery commission. If the qbit reads YES then the consequence is we will be happy and wealthy. Evolution by the Schroedinger equation leads quickly to a state in which we own five houses, a 200 foot yacht and an airplane. If we read NO on opening the qmail we are left poor.

So on these two eventualities the state of the world may be one in which the qbit read YES and we are wealthy. Or it may be one in which the qbit said NO and we are poor. We could imagine living in a world described by either of these states.

We can now apply the basic axiom of quantum mechanics which says that for any two states, the sum of these is also a good state. We have gotten used to quantum systems being in superpositions, but what about ourselves? But if quantum mechanics

applies also to us and our quantum computer then there are lots of states of the world which are possible sums or superpositions of the state in which the qbit says YES and we are rich and the state in which the qbit said NO and we are poor.

Now, we ourselves have never experienced being in a sum or superposition of states, each one of which is definite in the sense that it is a state of affairs we can recognize. Physicists have observed lots of quantum states in superpositions and they have never experienced themselves going into a superposition. Instead, what they have experienced is either getting one definite answer or the other. Moreover, if they do an experiment over again many times they notice that the proportion of the two different states is related to the square of the amplitude of the quantum state to be in the two situations.

What we have here is a big mismatch of theory and observation. Indeed, two big mismatches. The theory predicts we should be in a superposition of states we have experienced, and this never is experienced. What we see is a probabilistic outcome—sometimes one way, sometimes the other, but always definite. This is what we experience but it is not what the theory predicts.

The sober response is that a theoretical hypothesis has just been falsified. Since quantum mechanics works well so long as we don't include ourselves in the quantum system, what is being falsified is the combination of two hypotheses: first, that we and our measuring instruments can be included in the quantum state description. Second that the quantum state corresponds to the reality of the situation.

There is no problem if we take the quantum state corresponds only to knowledge that some observer has about a system, that will permit them to compute betting wagers. If I am part of the quantum state then it doesn't give betting probabilities for me, but it will give betting probabilities for you. It tells you how to bet on the chance that I am now rich as a result of playing the qlottery.

Nor is there a problem if we take the quantum state to be an incomplete description which corresponds to a very large ensemble of similar experiments. The quantum state in which I am in a superposition of rich and poor just corresponds to a situation where I have a finite probability of being either.

If this is right, I both do and don't win the qlottery. There is a branch where I do and a branch where I don't.

Another of the problems with this approach is it doesn't tell me how to define the branches. Why rich and poor? Why not one superposition of rich and poor versus another? Still another issue is that since every possibility is realized on some branch, there is no meaning to probability. How is it that quantum mechanics gives probabilistic predictions that agree with the predictions of quantum theory. For example, the fact that the statistical predictions of quantum mechanics are confirmed cannot count as

evidence for the theory because there are branches where, according to the theory, the statistical predictions of quantum mechanics are violated.

This is like the problem of whether 37 out of a hundred coin tosses being up would disconfirm a prediction that a fair coin produces 50% heads. But it's much worse, because if one goes to the limit of infinite numbers of observations, one ends up with an infinity of branches where the predictions of quantum mechanics are obtained. But the number of branches where the predictions of quantum mechanics are violated also increases to an infinite number. When they were still finite the first class was larger than the second, but you couldn't conclude anything definitive with a finite number of cases. But once you go to infinity all quantities are infinite which means equally large. You can no longer say that branches where quantum mechanics is violated are less common than branches where the predictions are satisfied.

Then there is the puzzle of what happens to one's consciousness each time the universe splits. Do we split too, so that versions of us experience all branches? Or does our conscious experience just go down one branch each time, leaving an infinitude of other branches populated by zombies? In that case I am likely to be the only truly conscious being in my branch, as each time the world splits so do the consciousnesses.

Roger Penrose used to ask how can you tell that a friend of yours who you thought was conscious has just turned into a zombie in your world? You can tell because he announces he believes in the many worlds interpretation.

The many worlds interpretation is what you get when you take quantum mechanics seriously as a realistic, final theory, which can apply to the whole universe. The collection of troubles and quandries the approach leads us to adds up to a strong argument to reject the premise that quantum mechanics is the final or universal theory. For all these issues can simply be avoided by taking the modest and reasonable stance that quantum mechanics is an approximation to a deeper cosmological theory, one that only makes sense when applied to subsystems of the universe.

A perhaps impolitic way to put it is that the issues the many worlds interpretation force us to contemplate have a bad smell to them. They appear profoundly fundamental. It appears that the very notion of reality is at stake. But there are never any actual consequences for understanding a real physical phenomena, or interpreting or predicting the outcome of experiments. No experimental result actually depends on whether quantum theory can be applied to the whole universe or not, at least in the way contemplated by the many worlds interpretation. Everything that quantum mechanics actually does for science can be done with much less extravagant hypotheses, such as Bohr's pragmatic language therapy.

In the end the many worlds interpretation seems to be like those solicitations for travel to far away vacation spots to view beachfront condominiums. What is promised is extravagant and heavenly. What is delivered is a sales pitch for something you have no use for anyway.

History alone would council modesty here. Each major new theory in physics, however dramatic its initial success, turned out to apply only in a limited domain. Whatever that domain was, it worked well there, but this did not prevent it from turning into nonsense when it was taken outside of its domain of validity. In the case of quantum theory the domain of validity appears to be small subsystems of a larger universe; these subsystems not including observers and measuring instruments.