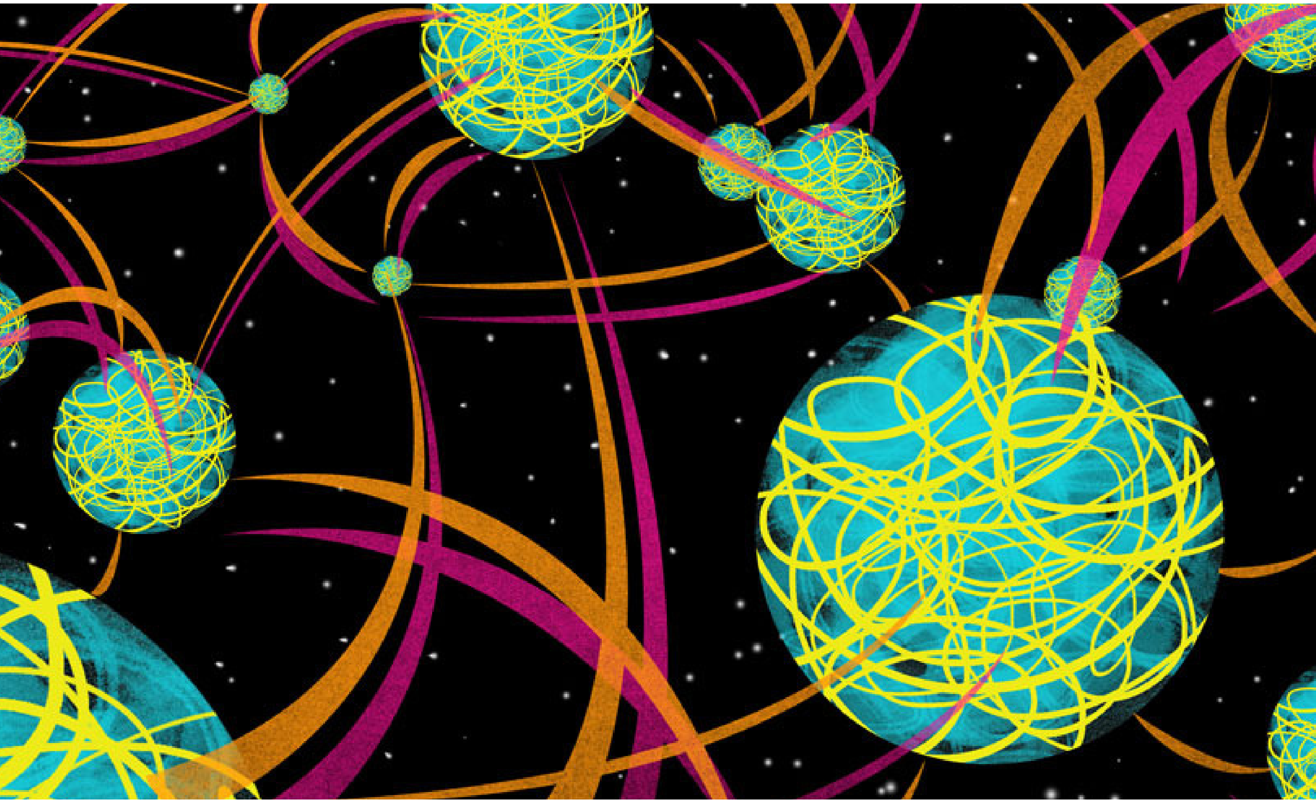
The Many Worlds Interpretation:

A CASE FOR THE SIMPLEST THEORY OF THE QUANTUM WORLD



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The Need for an Interpretation

Quantum theory has proven itself a strong mathematical model of the subatomic universe, with predictions of accuracy far superseding that of any other theory. Its power of prediction has led to our understanding of atomic, particle and nuclear physics, and has even paved its way to commercial use through the invention of the transistor. Despite its power and depth, the very foundations of the theory continue to prove illusive and difficult to settle. With over a century since its inception, the physics community still struggles to agree on the axioms defining quantum theory.

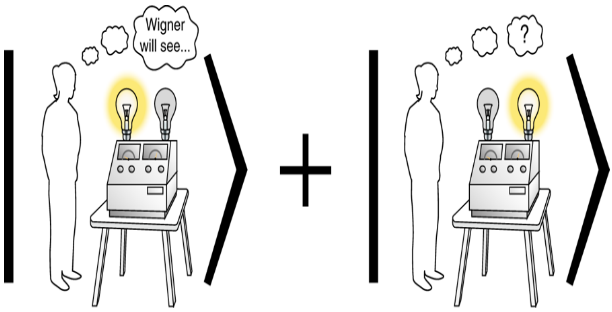
Unfortunately, the problem of understanding the axioms of quantum mechanics has found itself relegated to a problem of subjective interpretation. This relegation is in part due to the sheer effectiveness of the 'shut and up calculate' approach, as described by Mermin (2018). It is also due to the fact most interpretations tend to end up with similar predictions if they aim to fit the data. Yet the similarity of predictions does not mean all interpretations are born equal. Some interpretations are simply inconsistent, while others are too ambitious. However, if we hope to solve the big problems in quantum mechanics, ones that are mired in entanglement and decoherence, we need to have a quantum theory that has the necessary grounding to deal with such concepts.

In this article, the Copenhagen interpretation's shortcomings are presented and the interpretation is shown to be simply inconsistent. We then make the case for the many worlds interpretation as an alternative. The key statements of the theory are tackled through thought experiments, while the challenges and implications are discussed from the point of view of theoretical physics.

Failure of the Copenhagen Interpretation

The standard interpretation of quantum mechanics is the Copenhagen interpretation. It proposes that a quantum system is completely describable by its wavefunction. This wavefunction, left undisturbed, will exist as a weighted superposition of all the possible states of the system. However, when a measurement occurs, the quantum system will collapse into one of its possible states with a probability completely determined by the wavefunction. Despite the importance of measurement in this interpretation, the Copenhagen interpretation fails to define precisely what a measurement is. This inconsistency proves the Copenhagen interpretation incapable of providing a complete description of quantum theory. One thought experiment, first devised by Hugh Everett and Eugene Wigner (Boughn 2018), elucidates this problem.

Suppose your physicist friend is in a laboratory, measuring the z-component of an electron's spin using a measurement device. The device points up if an up state is measured, and down if spin state is down. You are outside the laboratory and completely unaware of the details of the experiment.



Wigner's friend, the original friend in the experiment, sees either an up or down electron upon performing the experiment. Yet the state of the friend relative to Wigner, outside the lab, is in a superposition of the two possible measurement states. Such contradictions are at the heart of the Copenhagen interpretation's inconsistency. Image credits to Pusey (2018).

The wavefunction that describes your friend's electron maybe written as

$$\Psi_{electron} = \alpha \left|\uparrow\right\rangle + \beta \left|\downarrow\right\rangle \tag{1}$$

with $|\uparrow\rangle$ and $|\downarrow\rangle$ being the up and down spin states of the electron. Copenhagen interpretation tells us the probability your friend observes the electron in an up spin state is $|\alpha|^2$, and for observing a down spin state it's $|\beta|^2$.

The wavefunction that describes your friend's laboratory system has two possible states. The first state corresponds to your friend observing the device point upwards with the electron being in an up spin state. The second state corresponds to a down state measurement. To someone outside the lab, the wavefunction of the laboratory system must take the form:

$$\Psi_{Lab} = \alpha \left|\uparrow\right\rangle_{Friend} \otimes \left|\uparrow\right\rangle + \beta \left|\downarrow\right\rangle_{Friend} \otimes \left|\downarrow\right\rangle \tag{2}$$

With the two terms corresponding to the electron having an up or down spin($|\uparrow\rangle$ or $|\downarrow\rangle$) and the friend observing the device point up or down ($|\uparrow\rangle_{Friend}$ or $|\downarrow\rangle_{Friend}$). The wavefunction will exist as a superposition of these possible states until something external to the lab performs a measurement on it.

From your friend's perspective, however, the wavefunction of the electron collapses as soon as the experiment is performed. This will lead the device to point in one direction or another, therefore the wavefunction of the lab system collapses to one of its possible states without anyone outside the lab 'measuring' the system. That implies that the lab's state is described by two wavefunctions! One of which is a superposition of the two up and down states, as it appears to you outside the lab, while the other is either the up or down state of the lab wavefunction, as it appears to your friend within the system.

The inability of the Copenhagen interpretation to define the wavefunction for a complex system like this is inconsistent with it supposing that the wavefunction of any system completely defines that system. After all, these two wavefunctions are physically different and therefore can not be describing the same system.

The Universal Wavefunction

The problem the Copenhagen interpretation presents is one of wavefunction collapse. The interpretation's inability to define what a measurement precisely is, and how a measurement leads to the collapse of the wavefunction, deems the Copenhagen interpretation unlikely to be the complete description of quantum theory. These complications all but beg the question, do we really need the idea of wavefunction collapse?

In 1957, Hugh Everett III, a PhD student of John Wheeler at Princeton, dared ask the question: What would a quantum theory look like if there was no wavefunction collapse? This suggestion, reminiscent of Einstein's decision to do away with lumeniferous ether, proved to have revolutionary consequences (Everett 1957). As the wavefunctions of individual particles and fields do not collapse, there must exist a universal wavefunction that describes all such particles and fields at all times! It must describe all their possible states and their entanglements with one another. This is a fully deterministic wavefunction that evolves according to Schrodinger's equation and, most importantly, never collapses. This idea of a universal wavefunction proves to be a central point in the many worlds interpretation.

Everett is credited with founding the many worlds interpretation along with John Wheeler. The bizarre implications of his theory led to his rejection by the physics community after his PhD. Now, his interpretation stands to be the most favoured interpretation in cosmology and second most favoured generally by theoretical physicists (Byrne 2008). Credits: CC BY-SA 3.0.

Decoherence and Branching of the Universe

To see the interpretation in practice, we refer back to our friend in the lab measuring the electron's spin. Upon measurement, the wavefunction of the friend and the electron entangle. The friend can't observe the device to point up if the electron has spin down and vice versa, therefore, the observation state of the friend is entangled with the spin state of the electron. This means we get the same wavefunction we had before:

$$\Psi_{Lab} = \alpha \left|\uparrow\right\rangle_{Friend} \otimes \left|\uparrow\right\rangle + \beta \left|\downarrow\right\rangle_{Friend} \otimes \left|\downarrow\right\rangle \tag{3}$$

Copenhagen would have told us that the friend can only be in one of those states once they perform the experiment and the wavefunction collapses. But Everett's interpretation takes away such collapse. The friend continues to exist in this superposition of states, with a spin up state and a spin down state. But this is markedly not what the friend sees! They do not see the device's pointer in some superposition of up or down. How can we reconcile this with the friend existing in a superposition of states? Decoherence comes to the rescue!

Everett (1957) tells us that everything evolves according to the universal wavefunction. In order to consider the whole universe, we suppose the universe is composed of the electron, the measuring device, the friend, and everything else outside the lab which we shall call the environment. Upon measurement, our friend does not just manage to entangle themselves with the electron, but in fact, they unwittingly find themselves entangled with the rest of the universe too. The wavefunction of the universe can be written as the sum of two terms:

$$\Psi_{Universe} = \alpha \left|\uparrow\right\rangle_{Environment} \left|\uparrow\right\rangle_{Friend} \left|\uparrow\right\rangle + \beta \left|\downarrow\right\rangle_{Environment} \left|\downarrow\right\rangle_{Friend} \left|\downarrow\right\rangle \tag{4}$$

Similar to before, the first term corresponds to the electron having spin up and the friend measuring that to be the case, but with the addition to the environment also registering that the electron is spin up. The second term corresponds to the down state equivalent. We omit the tensor product sign for compactness.

How does the environment register the friend's measurement and gets entangled with them? The answer lies within the universal wavefunction! Everything in the universe evolves according to this universal wavefunction, everything is quantum mechanical! There simply can't be a state in which the electron is spin down yet the rest of the universe behaves as if the electron's spin was up, that would be unphysical. The wavefunction then implies that the electron's state, as well as your friend's state, are all entangled with the state of the rest of the universe upon measurement. This phenomenon is what's called decoherence, an idea that's used in most interpretations of quantum mechanics that actually aim to explain or refute wavefunction collapse.

Any such entanglement with the environment, as Everett (1957) and others were able to prove, would produce orthogonal states which are called branches, i.e. states that can not interact or affect one another. So despite the superposition of the states, the friend does not see a superposition of pointers up and down. Instead, the friend finds themselves in one of the two branches with a definite measurement, and with no ability whatsoever to interact with the other branch that represents the other orthogonal state.

This idea neatly solves the paradox. For both you and the friend, there is only one wavefunction, the mother wavefunction of the entire universe. Once the measurement is performed, the friend is entangled with the electron and the rest of the universe and, unknowingly, exists in a superposition of two states of the universal wavefunction. As for you, sitting outside the lab, you would have no problem with the friend existing in a superposition of the two states, much like Schrodinger's cat. However, should the friend communicate with you which way the device points, you shall find that, like the friend, you have entangled yourself with the system and can only experience one of the branches, and not both at the same time.

Relativity of States

An important aspect of this interpretation is the idea of relative states. In the context of the thought experiment: If the electron has an up spin, the only possible observation the friend can make is to see the device point up. Therefore, we say that the state of the friend relative to the electron's up spin state is to observe the device point upwards. Understanding relative states is important because the friend, or any observer for that matter, never observes the universal wavefunction. Instead, what observers experience when they make a measurement is their state relative to one of the outcomes they measure.

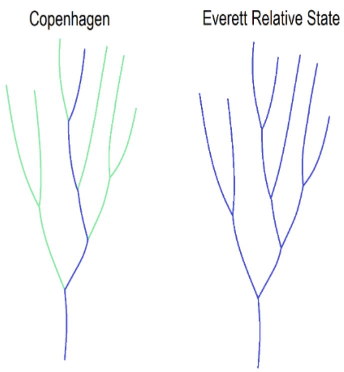
This idea of relative states enables us to correspond the interpretation to experience, and gives us a framework to discuss probabilities (Boughn 2018). While the universal wavefunction is completely deterministic, still one may ask 'what's the probability I will experience a certain relative state when I make a measurement?' It is also important to note that this relativity does not arise because of some wavefunction collapse, but because we are not able to observe orthogonal branches of the universal wavefunction.

The Many Worlds: Predictions and Difficulties

The Many Worlds

Everett's interpretation has a striking implication: all states of every wavefunction are equally real in some branch of the universe! This idea is the main reason Albert and Loewer (1988) dubbed it 'The Many Worlds' interpretation of quantum mechanics. However, Everett's idea was not to add many worlds to the mix to solve any problems, but rather to assume that the wavefunction does not collapse, and from that everything followed.

Any interpretation that assumes that a wavefunction collapses to one of its states is smuggling in the assumption that the information in all the other states is deleted, thus actively erasing most of the possible worlds (Saunders 2013). But what justification do we have to do that? In this sense, the many worlds are a prediction that follows the basic assumptions of a self-consistent interpretation of quantum mechanics.



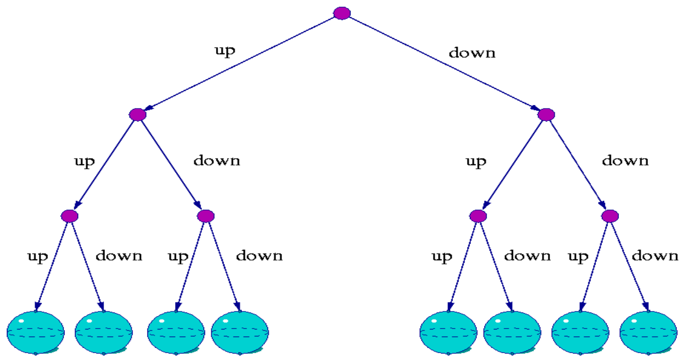
The Copenhagen interpretation assumes just as many states as the many worlds interpretation. However, upon measurement, it deletes all the other states, as shown in green. Everett's interpretation maintains them all by avoiding wavefunction collapse. Credits: (Susskind 2016), Stanford University

The Probability Problem

One of the main difficulties the many worlds interpretation faces is the fact it is deterministic. How can a deterministic universe produce the quantum statistics we observe in the lab? Everett was able to foresee the problem, and presented a somewhat atypical solution. His solution was to assign a measure, or a degree, of typicality to each branch of any arbitrary wavefunction based on the coefficient associated with it (such as α and β in the previous example). This typicality measure describes the probabilities you will end up with a given measurement result on some branch. He was then able to prove that in most typical branches, the observer would observe the same quantum statistics i.e. squaring the amplitudes for probabilities, when it came to measuring states of relative wavefunctions.

Everett designed another thought experiment to explain this result. Imagine a quantum mechanical measurement device that measures the spin of a given electron each run. There are many of these electrons, prepared for each run. The machine runs the experiment N times and stores the values. Each measurement is a measurement of the wavefunction of the electron's spin relative to the branch it is in.

Assuming there are equal probabilities of up and down states being measured, we would expect to measure N/2 up spins and N/2 down spins with some standard deviation. Using the idea of a measure of typicality based on how these branches entangle with the environment, Everett (1957) were able to prove that 'typical' branches would observe these statistics. There will be branches which will observe all up or down states, after all these are possibilities that must be realised. However, he was also able to prove that typical branches will dominate as N goes to infinity. Others, such as Deutsch (1999), were able to derive quantum statistics in all branches using ideas from decision theory.



The tree in the figure shows all the possible branches of the universe for a machine measuring the spin of an electron 3 times. As all branches are equally real, two of the branches will measure all up or all down, which deviates from the expectation values of quantum statistics. Most will, however, measure the expected statistics. CC BY-SA 3.0.

Putting the Theory to the Test: Extracting the Universe from the Wavefunction

The problem of probabilities is not the only criticism the theory faces. The main criticism most interpretations face is the difficulty of testing them. The most promising idea in terms of the testability of the theory comes from Sean Carroll, the Feynman Professor of Physics at Caltech, and his colleagues Cao, Carroll, and Michalakis (2017). What if we were able to derive the properties of the universe, such as quantum gravity, from the universal wavefunction? Carroll believes this is possible. This would solve the quantum gravity problem from the opposite, hopefully easier, direction. Instead of quantising a gravitational field, gravity and the geometry of the universe is derived from the quantum mechanical state of the universe.

As all the wavefunctions that compose this universal wavefunction live in a single Hilbert space, it may be divided into certain subspaces. Carroll then defined a 'distance' between these Hilbert subspaces via a measure of the entanglement between the wavefunctions living in them. This measure between subspaces can be found by looking at the shared information or entropy between them. Carroll et al. were then able to prove that such measure of distance is dynamic, as the entanglement between the subspaces will vary from place to place. They then found that if we look at the geometry induced by this measure of distance, and the energy associated with these subspaces, Einstein's equations of gravity appear to be the geometric governing equations of the space! We end up with Einstein's equations after starting with quantum mechanical notions.

While this still needs more polish as a theory, it is a strong indication that our choice of quantum interpretation is a vital ingredient in determining how we progress in developing quantum theory itself. Most importantly, if this theory is to be proven mathematically or experimentally, it would offer strong indications that an interpretation that doesn't accommodate wavefunction collapse and embraces a universal wavefunction is likely to be true. That would put the many world interpretation in great footing as the fundamental basis for quantum mechanics. It would also present a way of solving quantum gravity, which would be great.

Conclusion

Everett's interpretation is by no means complete. It leaves much to explain, probabilities in a deterministic universe and how branches lead to the classical world are two prominent examples. Despite that, and despite having mind bending conclusions, the many worlds interpretation is in a respect the simplest interpretation of quantum mechanics. It relies on the same fundamental assumptions most interpretations make, except it makes one less assumption: wavefunctions don't have to collapse. A universal wavefunction, an infinity of worlds and a deterministic universe are what we get if we respect the Schrodinger equation and allow it to govern the dynamics of the universe without collapse. In the words of Carroll (2018): 'Believing in the Everett interpretation is believing that the Schrodinger equation tells us how quantum dynamics work, without needing to change it in any other way. So it is the minimal interpretation.'

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