Nothing is Real

Word Count: 2569

Nothing is Real

Quantum mechanics is notorious in popular culture for one thing and one thing only – it's weird. Given its reputation for allowing particles to pop in and out of existence, spooky action at a distance, and allowing cats to die on the whim of bespectacled Austrian men, this is hardly surprising. Yet, it has always been revered by the scientific community as the most successful quantitative theory ever produced. As such, one should expect such a theory to really have a firm grasp on what the notion of reality is. One would think it's not much to ask from a discipline often quoted as man's greatest achievement (1); unfortunately, things aren't as rosy as they seem and when it comes to fundamental questions such as "what is real?" the most fundamental of all sciences falters. This article will explore some of the interpretations of quantum mechanics and how they seek to answer some of these fundamental questions.

The Wavefunction and Physical Reality

Before even beginning to think about the implications for reality as a result of quantum mechanics, one must first consider the way in which quantum mechanics seeks to explain physical phenomena and thereby reality. The bog-standard method to do this has always been to evoke the use of a mysterious entity called the wavefunction, ψ – perhaps the cornerstone for everything quantum. All quantum mechanics requires of a wavefunction is that it satisfy Schrödinger's equation outlined below.

$$\hat{H}\Psi = i\hbar\frac{\partial}{\partial t}\Psi$$

Schrö dinger's time dependent equation

Born's rule often crops up as the most intuitive way to think of the wavefunction which states that the modulus squared, $|\psi|^2$, of this quantity represents the probability density of a particle described by that wavefunction (2). The form of the wavefunction itself is a linear superposition of eigenstates but crucially the wavefunction does something odd upon observation (i.e. measurement) of a quantum system; it collapses to just one of these eigenstates which corresponds to what an observer finally sees (3). This short outline of the wavefunction and its collapse already sets alarm bells ringing and begs so many questions: what's happened to those other eigenstates, why does the act of observation cause the wavefunction to collapse, and does the wavefunction represent a physical reality that is tangible to observers? Unfortunately, these questions which immediately spring to mind remain unanswered 86 years after the Nobel Prize in Physics was awarded to Werner Heisenberg for the "creation of quantum mechanics" (4).

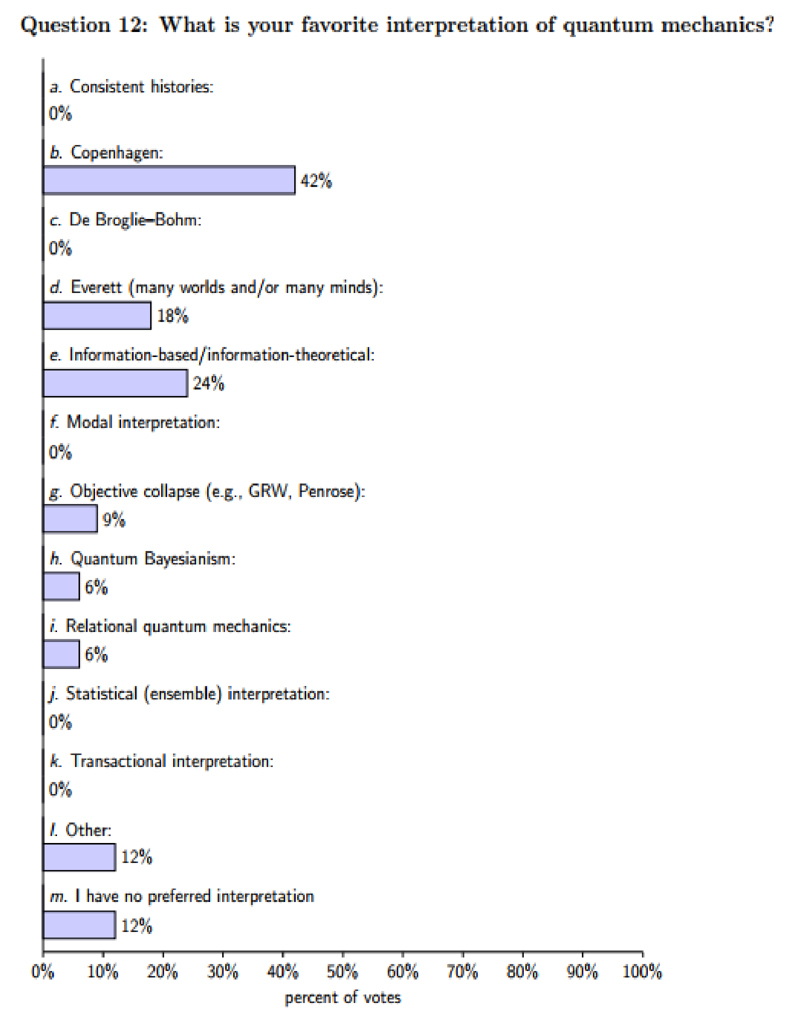

Figure 1: Graph showing results of survey taken in (5).

Quantum mechanics' inability to answer these questions then leaves room for interpretation with regards to what is considered to be reality and what is not and the last 86 years have seen countless interpretations of wavefunction collapse. Brilliant! Surely in all those years the scientific community has come to some sort of consensus and has confidence in one of these interpretations and is just waiting for the right technology to come along to test this, right?! Regretfully, my excitement is unwarranted and thus far there is no consensus. A 2013 paper entitled "A snapshot of foundational attitudes towards quantum mechanics" surveyed 33 participants at a conference on the foundations of quantum mechanics. Figure 1 shows the outcome of a particular question of interest: "What is your favourite interpretation of quantum mechanics?" The results are astonishing; not one interpretation has accumulated over half of the votes and gained a clear majority. Quite frankly, these results are a stain on mankind's greatest theory given the number of years since its supposed inception and the lack of consensus indicates a deep uncertainty in quantum mechanics. In order to appreciate why this disparity of opinion exists, the 3 most highly rated interpretations according to the above survey will be discussed in more detail: the Copenhagen interpretation, the Everett (many-worlds interpretation), and the quantum informational interpretation.

The Interpretations of Reality

The Copenhagen Interpretation

The textbook interpretation of quantum mechanics has stood the test of time first being developed by Werner Heisenberg and Niels Bohr in the 1920s (6) and still remaining the most popular interpretation amongst the physicists surveyed in the 2013 paper above. The Copenhagen interpretation is funnily enough equivalent to the physics discussed in the last section when introducing the ideas of the wavefunction and wavefunction collapse – just going to show how deeply rooted it is in quantum mechanics and why it might still be so popular to this very day. The Copenhagen interpretation is built up on 3 primary postulates (7):

- The wavefunction is a complete description of a quantum system
- When a measurement is made of a quantum system described by a wavefunction, said wavefunction collapses to one state
- If two properties are incompatible, no measurement can determine both properties to a greater precision than allowed by Heisenberg's uncertainty principle

Inherent to the Copenhagen interpretation is the notion that on a quantum scale, reality is probabilistic, this is what was captured by Born's rule discussed in the first section. This immediately rips the idea of determinism out of quantum theory and represents a sharp divide between what is expected from classical and quantum physics. However, I believe the fundamental flaw in this interpretation is in the way it treats wavefunction collapse. It has been established that the wavefunction is a linear superposition of eigenstates, this can easily be digested using the classic double slit experiment which demonstrates wave-particle duality (a schematic for which is seen in figure 2 below).

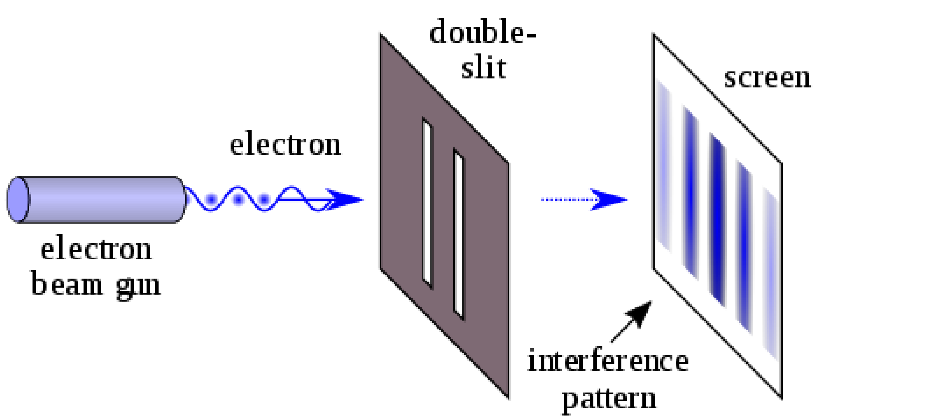

Figure 2: The experimental setup for a typical double slit experiment (8).

Let's suppose there are 2 eigenstates, one representing an electron wave and one representing an electron particle. The interpretation says that on observation of this system, the wavefunction will collapse to one of these realities as if the other never existed. However, in the double slit experiment we see both of these realities coming to fruition. Electrons are fired as particles through the double slit and observing either of the slits shows that the electrons do indeed go through the slits as particles. However, the wave nature of the electrons is also clearly apparent due to the interference pattern observed on the screen! Therefore, for the interpretation to disregard either the wave or the particle reality at any time given that both clearly exist seems a little strange. The connotation here is that the universe makes a decision between the wave reality and the particle reality and the result of that decision is ultimately what is observed. Naturally, a decision-making universe sounds odd and raises far more questions than it answers. The next interpretation seeks to address this major issue with the Copenhagen interpretation.

The Everett (Many-Worlds) Interpretation

The many-worlds interpretation was formulated by Hugh Everett in 1957 as part of his PhD thesis. This interpretation rejects the postulates laid out by the Copenhagen interpretation and the very idea of wavefunction collapse. It looks to resolve the issues with the Copenhagen interpretation by introducing the universal wavefunction: one that describes the totality of existence and treats the entire universe as a quantum system (9). In many-worlds every time a

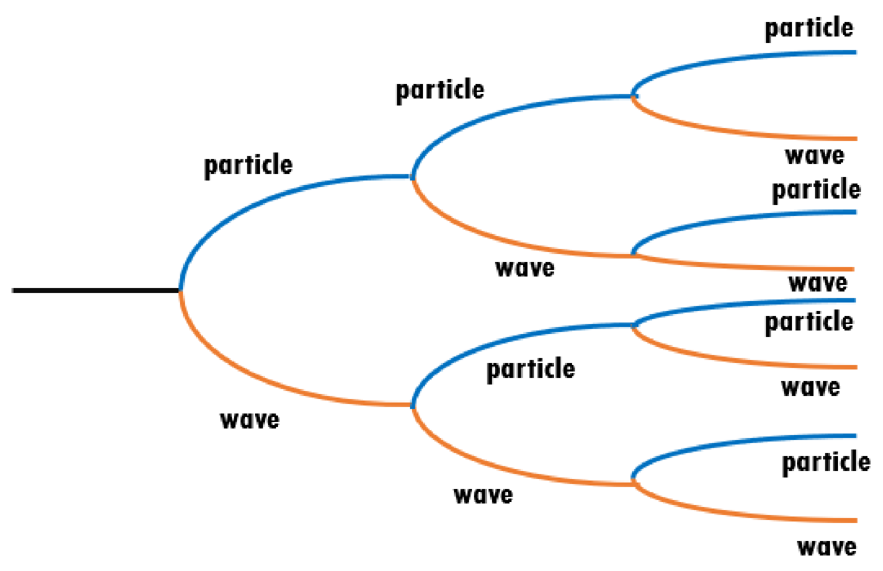

Figure 3: Diagram indicating what a multiverse based on several particle-wave superpositions could look like where each node represents an observation.

measurement is made, wavefunction collapse does not occur but rather the universe branches off into the possible realities that could have been observed. Many-worlds in essence evokes the existence of many parallel universes where every possible eigenstate that has ever existed evolves according to Schrödinger's equation in a self-contained reality – it also postulates that all of these realities are equally valid and occur just as any other. All these possibilities and universes are contained within the universal wavefunction itself. A diagram of what a series of particle-wave superpositions could lead a multiverse to look like is seen in figure 3.

To further understand what many-worlds is trying to convey, consider the example of the double slit experiment again. The observation made at the double slit resulted in a collapse according to the Copenhagen interpretation and the electrons were found to be particles at this juncture. However, many-worlds says that this was just one of two possibilities, given that there was a superposition of a particle and a wave at this point, and that there exist parallel universes in which the electrons were observed as waves also.

Many-worlds boggles the mind as it requires the existence of a ludicrously large number of, if not infinitely many, universes whose realities never interact with one another. There is also the issue of a fundamental principle in physics: conservation of energy. How is this not violated if all the matter in the universe is copied and recreated every time a superposition of states results in a new branch on the multiverse tree being created? While the many-worlds interpretation does a lot to solve some of the puzzling paradoxes that arise from the Copenhagen interpretation, it is not perfect and raises just as many questions as any other interpretation. Furthermore, given its implications of a multiverse filled with parallel universes that don't interact with one another, how could one possibly test the existence of any of these other universes and verify the existence of the multiverse? Its inability to be a testable theory given what is currently known is disconcerting and does not help the case for many-worlds to be the correct interpretation of reality.

Quantum Informational Interpretation

Perhaps the most unique out of all the interpretations that will be discussed here, quantum information theory is an incredibly active field which looks to completely revolutionise the modern world with the potential onset of quantum computing coming as a direct consequence of it. While quantum information theory is ushering in a new technological era, it can also provide fresh insights to some of the old problems that have been discussed.

Quantum informational interpretations are primarily based off one assumption in particular, a quantum state is just a representation of knowledge or information about the system it is describing rather than a wavefunction with physical properties as has been previously considered above. The wavefunction is related to the quantum state in the following way: $\psi(\mathrm{x}) \equiv \langle \mathrm{x}|\psi\rangle$ (10).

In order to address some of the problems being discussed, take the case of the double slit experiment once again. The quantum informational interpretation says that nothing can be said of the electrons' physical properties as they pass through the slits because the quantum state does not define this but rather the information does. With this approach, the interference pattern is caused by the interference of information and not physical interference of the electrons themselves. The state simply describes an abstract probability of finding the particle somewhere in the setup (11). So rather than dealing with a physical object collapsing, the thing collapsing is information itself (the abstract probability). This is a lot easier to understand because it is understood how probabilities collapse. Suppose a standard six-sided die is rolled and the number 1 shows up. Instantly, the probabilities of 2-6 showing up vanish and are equal to zero and these probabilities are said to have collapsed. In the same way, when the quantum state collapses, no physical exchange is occurring but rather the information encoded by that quantum state is changing and this correlates with what an observer finally sees. In the case of the double slit experiment, the superposition of wave and particle only collapses because the information describing that state has changed rather than anything physical changing.

However, there are issues with this interpretation also. A 2012 paper presented a no-go theorem which spells disaster for the notion of only information being exchanged at collapses. The paper says, "if the quantum state merely represents information about the real physical state of a system, then experimental predictions are obtained which contradict those of quantum theory" (12). This indicates that quantum states cannot be purely informational and must have some physical aspect to them.

Nothing is Real

All the above interpretations were laid out to do the same thing, explain what physical reality actually is on a quantum scale and why observers observe what they observe. All of them achieve this to some extent but all the interpretations have their own shortcomings also. This article has only looked at 3 interpretations in detail but there are countless others as can be seen from Figure 1. Perhaps the fact that each interpretation has shortcomings and given the sheer number of them explains the disparity of opinion amongst the scientific community with regards to which is correct. The disparity of opinion however may be pointing to a deeper, underlying issue with the current formulations of quantum mechanics itself. Could it be that there is not a complete description of reality that quantum mechanics in its current form can provide? Albert Einstein was certainly a proponent of this idea. In a paper of 1935, Einstein showed along with Podolsky and Rosen that the wavefunction cannot provide a complete description of reality (13). However, the consensus amongst the scientific community now is that many of Einstein's later ideas on quantum mechanics were in fact wrong (this can be seen through the results of another question asked in the survey conducted in (5)). Given the man's track record on all things physics thus far however, it would be criminal to ignore his views on the wavefunction and reality. The paper remarks in its conclusion with regards to a complete description of reality, "we left open the question whether or not such a description exists. We believe, however, that such a theory is possible." Whether or not Einstein, Podolsky, and Rosen are alluding to this theory being built up upon quantum mechanics or being entirely fresh, new physics remains unclear in this paper, but it does beg the question: can the current formulations of quantum mechanics achieve this description?

In the 86 years since the Nobel committee honoured the creation of quantum mechanics and in over the century of work done surrounding the discipline, one is still left with an incomplete description of reality. This is somewhat an embarrassment for mankind's greatest theory. Yes, quantum mechanics has been rigorously tested and produced beautiful results that are numerically accurate, but it is worth noting that this is not dissimilar to the hold classical physics had on the scientific community for centuries. Newton laid down the foundations for all of physics with a theory that seemed so triumphant when it was first proposed in the late 17^{th} century. It was rigorously tested and produced accurate results for centuries. Classical physics had its shortcomings however, it was unable to explain the orbit of Mercury for example. But this shortcoming helped physicists of the day realise that there probably was something wrong with their current formulations and that the theory either had to be modified or changed completely. At the turn of the nineteenth century, all it took was an Albert Einstein and a quantum revolution to turn classical physics on its head. What I'm trying to say with this laboured anecdote is that the warning signs for quantum mechanics being inadequate in its current form are there, its inability to achieve a complete description of reality should set alarm bells ringing for the scientific community. Perhaps it is high time we let go of our current formulations of quantum mechanics - just like the boy physicists of the 1920s did with classical mechanics - and spark the next big revolution in physics.

Acknowledgements

With thanks to my family for the copious amounts of food that kept my energy up when reading about this topic, my friends for their continued support, and to John Lennon for writing *Strawberry Fields Forever* and giving me a cool title.

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Nothing is Real – Article Plan

Aim: Outline to the reader the disparity of opinions about physical reality on a quantum scale. Give the reader an appreciation of what is meant by wavefunction collapse and introduce 3 of the interpretations of physical reality that follow from this phenomenon. The overall scope of the article will be to convince the reader that in the century of work that has been done on quantum mechanics, we are no closer to finding out what reality is and that we might not ever get to such a point.

Section 1 – The Wavefunction and Physical Reality ≈ 600-700 words: Give the reader an overview of what is understood about the wavefunction thus far and what is meant by *reality* in physics. Give a non-exhaustive introduction to wavefunction collapse and how this leads to many different interpretations in quantum mechanics. Outline the disparity of opinions with regards to which interpretation is correct (assuming any of them are correct). Argue that the disagreement among the scientific community is embarrassing given the number of years spent developing quantum mechanics and could be pointing to the fact that we may never have a complete description of physical reality.

Section 2 – The Interpretations of Reality ≈ 1100 – 1200 words: Give the reader a brief overview of the three most widely accepted interpretations – Copenhagen Interpretation, Everett (Many – Worlds) Interpretation, and Quantum Informational Interpretation. The interpretations will be split into their own self-contained subsections with each subsection aiming to provide an insight into how each interpretation resolves the issue of wavefunction collapse and the explanation of physical reality it provides. Criticisms and refutations of each of the interpretations will also be given.

Section 3 – Nothing is Real ≈ 500 - 600 words: Summarise what all the interpretations of quantum mechanics aim to achieve. Argue that the number of interpretations and disagreement among the scientific community may be pointing to a deeper underlying issue in quantum mechanics itself and could be because there really is no complete description of physical reality that quantum mechanics can provide (in the same vein as Einstein). Alternatively, if there is a complete description of reality that can be offered by physics it is unachievable with its current formulations.

Conclusion ≈ 300 - 400 words: Final plea to the reader that in the century of work done on quantum mechanics one is still left with an incomplete description of reality regardless of how good the theory is at explaining physical phenomena. Argue that this is similar to classical mechanics' hold over physics for many centuries and how this formulation also proved to be incomplete. **This conclusion is subject to change depending on the research carried out between the planning stage and writing the article.*

Initial Reference List:

Pusey, M., Barrett, J. and Rudolph, T. (2012). On the reality of the quantum state. Nature Physics, 8(6), pp.476-479.

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Harrigan, N. and Spekkens, R. (2010). Einstein, Incompleteness, and the Epistemic View of Quantum States. Foundations of Physics, 40(2), pp.125-157.

An interesting article. Be careful that section 2 doesn’t just become three separate descriptions of interpretations – that might get dull for the reader. Think about what point you are trying to make in section 3. Is there anything to back up your arguments other than your opinions?