Will Advances in Quantum Computing Shed Light on Foundational Issues in Quantum Mechanics?

Or more specifically, is it worth getting excited about Deutsch's "three experimental implications" of the Everett interpretation?

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Why am I writing about this topic?

While taking a course on philosophical issues in quantum mechanics, I came across a 1986 article by David Deutsch called "Three experimental implications of the Everett interpretation." On the first page, Deutsch writes:

> *"It has come to my attention that there are still some conference participants who harbor residual doubts about the Everett interpretation of quantum theory. I thought it might be helpful to leave aside for a moment the theoretical arguments pro and contra (such as they are) and look at a seldom mentioned but important aspect of Everett's interpretation, namely its connection with experiment." (p.215)*

I was intrigued by this claim, especially after having been taught that Everett's interpretation wasn't experimentally verifiable. In slight disbelief, I jumped to the end of the paper and came across these passages:

> *"Experiment 3 is nothing less than a direct, unambiguous experimental test of the Everett quantum theory against any theory that has the wave function collapsing." (p. 216)*

There was no doubt that Deutsch was promising experiments. Could quantum computers really hold the key to the hidden mysteries of quantum mechanics? I decided to read the entire paper – and was immediately intimidated. The paper is filled with mathematical formalism, references to concepts in MWI that I had never heard of, and quantum algorithms that I had never learned. Nonetheless I resolved to understand what he had to say, and evaluate his claims myself. I asked myself the following questions:

1. *Do Deutsch's experiments make sense?*
2. *Do Deutsch's claims follow from his experiments?*
3. *Will quantum computing have anything to say about MWI?*

Who is David Deutsch?

David Deutsch is a physicist at Oxford who pioneered the field of quantum computation in the 1980s and 1990s. He is also an outspoken proponent of the many-worlds interpretation of quantum mechanics.

Who is my intended audience?

I am writing this for physics and chemistry majors, my peers at Columbia, and my professor David Albert (although I suppose that he has presented this material so many times that my presentation is dull in comparison). In particular, I have my "physics" friends in mind who might have studied quantum mechanics formally but didn't get a chance to think about some of the finer philosophical issues. I am also writing this for myself – I have recently found myself struggling to explain what I am studying to friends, and I am thankful for this opportunity to solidify my understanding and improve my exposition of all these issues (although I still have quite a ways to go). If this paper comes across as overly mathematical, I apologize – I figured that if Deutsch took the time to include mathematical formalism, I too should take the time to understand it and expound on it.

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There remain, after decades of progress in both theoretical and experimental physics, some unresolved foundational issues at the heart of the theory of quantum mechanics. The thorniest issue of them all is the 'measurement problem' associated with the infamous 'collapse' of the wave function. Various resolutions to this issue have been proposed; the Many Worlds Interpretation, Bohmian mechanics, and 'objective collapse' theories are among the more familiar and reputable ones. However, the powerful tools that quantum mechanics provides can be applied to a vast number of real problems in physics and chemistry without having to pay any sort of attention to philosophical problems in the quantum mechanical framework. So until recently, these foundational issues were confined to the realm of philosophers of science and a handful of curious physicists. How to interpret the collapse of the wave function did not, as far as most physicists were concerned, have any experimental implications.

The development of quantum computing as a serious area of research has brought foundational issues back into the spotlight – for the simple reason that wave function collapse is at the heart of quantum computing. *But how exactly will developments in quantum computing resolve these conflicting theories, if at all?* David Deutsch (1986) famously proposed three *gedanken experiments* involving quantum computers that point to the correctness of the Many Worlds Interpretation (henceforth MWI). However, in writing his monograph, he treated all competing theories as a single entity and avoided any discussion of the subtleties associated with distinct non-MWI theories. In addition to explaining and evaluating Deutsch's claims, this essay seeks to explicitly include objective collapse theories in Deutsch's discussion.

Part I reviews the basics of quantum mechanics and the Copenhagen interpretation. This section is crucial for the subsequent discussion, and assumes familiarity with quantum mechanics and linear algebra. Part II sets up the framework of the Many Worlds Interpretation, and Part III establishes the framework of objective collapse theories (how Bohmian mechanics fits in will hopefully be explored in a future installment). Part IV introduces basic concepts in quantum computing, and finally Part V analyzes all of David Deutsch's three proposed experiments with regards to the Copenhagen interpretation and objective collapse theories.

Here is a preview of the experiments:

Experiment 1: Your state of consciousness is different at time t_1 from its state at time t_2

Experiment 2: Run a simple quantum algorithm and explain how a single quantum computer can physically act like multiple classical computers running in parallel

Experiment 3: Use a quantum computer to play the ambiguous role of both observer and observed object. Do different theories present different outcomes?

Part I – Traditional Quantum Mechanics

The *wave function* lies at the core of quantum mechanics. The tension between the mathematical properties of the wave function (linear superposition) and certain aspects of physical experience (the absence of linear superposition) give rise to the *measurement problem* and the idea of *wave function collapse*. The traditional 'Copenhagen' interpretation of quantum mechanics dealt with the measurement problem in a philosophically unsatisfactory manner, essentially creating a dichotomous theory of physical systems and observers. As quantum mechanics matured, a handful of auxiliary theories sought to reinterpret the measurement problem and therefore the mathematical framework of quantum mechanics. But before jumping to these theories, it is important to review the mathematical framework of quantum mechanics and describe the infamous measurement problem.

The wave function is a complete description of the *quantum state* of a particle, and the *Schrödinger equation* (not shown) describes the behavior of the wave function in space and time. The Schrödinger equation is a mathematical "wave equation," i.e. a second-order linear partial differential equation. The set of all possible wave functions forms an abstract mathematical vector space called a "Hilbert space." It is possible to add multiple distinct wave functions together to form a linear superposition that is also a wave function in the Hilbert space. This is represented mathematically as:

$$|\Psi\rangle = \alpha|\phi\rangle + \beta|\varphi\rangle \qquad \text{(I.1)}$$

where $|\Psi\rangle, |\phi\rangle$, and $|\varphi\rangle$ are quantum states, α and β are complex numbers. While this simple property has important effects on the theory of quantum mechanics, it is also the source of some tension.

Traditional quantum mechanics is sometimes presented in an axiomatic manner (see Vaidman 2002); this is perhaps the most appropriate way to lay bare the mathematical structure that is the basis of all *interpretations* of quantum mechanics:

<u>Axiom 1</u> – States of physical systems are modeled by normalized vectors in a Hilbert space. In this Hilbert space, linearity holds as in (I.1). In addition, the state *evolution* is linear such that if at time t_0 the wave function is represented by

$$|\Psi(t_0)\rangle = \alpha|\phi(t_0)\rangle + \beta|\varphi(t_0)\rangle \qquad \text{(I.2)}$$

at time t_1 the wave function is still a superposition

$$|\Psi(t_1)\rangle = \alpha|\phi(t_1)\rangle + \beta|\varphi(t_1)\rangle \qquad \text{(I.3)}$$

The wave function is also assumed to be the most accurate model of the state of a physical system. It follows from the mathematics that when particles interact, the quantum state of each particle must subsequently be described relative to the others and the particles become "entangled." This is mathematically written for two states $|\phi\rangle$ and $|\varphi\rangle$ as $|\phi\rangle|\varphi\rangle$ or $|\phi,\varphi\rangle$

<u>Axiom 2</u> – Observable quantities are represented by mathematical operators on the Hilbert space. Operators acting on wave functions form eigenvalue equations, and the eigenstates associated with a particular operator are the only possible measurable states. The *probability* of obtaining a particular eigenstate is associated with the absolute square of the eigenvalue (this is called the *Born Rule*). For example, the probability of obtaining the $|\phi\rangle$ eigenstate from (I.1) is $|\alpha|^2$ (See Deutsch 1985 for a slightly different set of axioms).

But where and what exactly is the tension? *The problem, of course, is that while it might be powerful to treat microscopic particles as wave functions with linear superpositions, this description doesn't seem to work for macroscopic objects. Intuitively there are no linear superpositions in the macroscopic world!*

The tension is best illustrated by the following example: How is a measurement process modeled according to the theoretical framework outlined above? Presumably there are two objects, a macroscopic measuring device and a simple particle. When the particle passes through the device, the device indicates whether the particle has a particular property – say whether it is in the $|\phi\rangle$ eigenstate or the $|\varphi\rangle$ eigenstate. However, according to Axiom 1, it is clearly possible to describe a particle as a superposition of eigenstates, as in (I.2). So what happens when a particle described by (I.2) passes through the device? If the measuring device is treated as a large quantum system that is in a single, observable "ready" state $|d_R\rangle$, and the particle is also in a single state $|\phi\rangle$, the measurement interaction is simply:

$$|d_R\rangle\,|\phi\rangle \text{ becomes } |d_\phi\rangle\,|\phi\rangle \qquad \text{(I.4)}$$

where $|d_\phi\rangle$ represents the device as being in the state of "having measured" $|\phi\rangle$. However, if the particle entering the device is in a superposition of both states, then the interaction is mathematically represented as:

$$|d_R\rangle\{\alpha|\phi\rangle+\beta|\varphi\rangle\} \rightarrow \alpha|d_\phi\rangle\,|\phi\rangle+\beta|d_\varphi\rangle\,|\varphi\rangle \qquad \text{(I.5)}$$

Which seems to imply that the device is *also* in a superposition of states. *But macroscopic measuring devices measure particles as single eigenvalues and not as superpositions.* The Born Rule states that the probability of observing the particle in the $|\phi\rangle$ eigenstate – i.e. of the device being in the state $|d_\phi\rangle$ – is $|\alpha|^2$. *So how does the device get from the superposition in (I.5) to detecting that the particle is only in one eigenstate?*

Paul Dirac famously proposed adding a postulate to the quantum mechanical framework that "a measurement always causes a system to jump into an eigenstate of the observed quantity." However, this hardly resolves the issue: this postulate breaks the linear nature of the theory and renders it useless for describing the physical world beyond the microscopic domain. In addition, just what a measurement is – i.e. *where* and at what *point* the system "jumps" into an eigenstate – is entirely ambiguous with no scientifically precise definition. Does the device cause the "jump" even though it is just an ensemble of particles? If so, how small does a device have to be in order for it not to cause a "jump?" And a measurement cannot simply be an interaction between ensembles of particles, as superposition does quite a good job at modeling ensembles of particles! Alternatively, claiming that the measuring device is in a superposition until a *human observer* looks at it is just as imprecise. Are humans therefore exempt from physical theory? And if a cat looks at the measuring device (or is somehow implicated, as in the Schrodinger's cat paradox), are the cat *and* the measuring device in a superposition until a human observes both of them? Without a clear definition of what counts as an observer, it is impossible to even describe a collapse mechanism.

And while the mathematical property of superposition and the related phenomenon of entanglement are mostly responsible for this philosophical mess, it is also the key to the success of quantum mechanics. This tension between the mathematical property of superposition and common sense observation that macroscopic objects are not in superpositions is the infamous measurement problem. However, despite the serious objections mentioned above, the idea that a measurement causes a system to jump into an eigenstate of the observed quantity became an accepted feature of traditional quantum mechanics.

What exactly a linear superposition *is*, besides the fact that it is a mathematical construct, is actually quite unclear as well. Is $|\Psi\rangle$ simultaneously both $|\phi\rangle$ and $|\varphi\rangle$? Is it *spread* between the two? The general consensus at the time these issues were first debated was that *nothing could be said about the physical reality of the system until it was measured.* While a particle might be modeled mathematically by a superposition before measurement, talking about the *physical properties* of the particle before measurement was meaningless.

These instrumentalist/positivist attitudes towards measurement and the physical meaning of superposition are features of the so-called "Copenhagen" interpretation, the school of thought associated with Niels Bohr and Werner Heisenberg. It is precisely the Copenhagen interpretation that MWI and objective collapse theories sought to replace.

Part II – The Many Worlds Interpretation

MWI is based on the simple assumption that the entire universe can be modeled by a universal wave function that obeys a deterministic wave equation. Just like a particle, the universe can be thought of as a superposition of real, existing, worlds. It follows that "our" world is one of an extraordinarily large plethora of similar and dissimilar worlds. Since an "observer" has no special status in MWI, there is no such thing as a wave collapse – instead, the world that the wave exists in splits into *multiple* worlds such that *all the possible outcomes of a quantum interaction are realized*. A measurement is therefore just an interaction, usually irreversible, between subsystems of the universal wave function that correlates the value of a quantity in one subsystem with the value of a quantity in the other subsystem. Such interactions cause a decoherence of the universal wave function into mutually unobservable but equally real worlds. According to Vaidman (2002), MWI is both a mathematical theory that addresses the time evolution of the universal wave function and a philosophical, metatheoretical framework that tries to match the mathematics of the universal wave function to everyday experience.

Interpreting the example of Schrodinger's cat according to MWI helps clarify some of the claims mentioned above. The cat is isolated from its environment in a sealed box with a device that might or might not release a lethal dose of cyanide, depending on the quantum state of the device. According to the Copenhagen interpretation, it is not possible to say whether the cat is alive or dead until a measurement is made, namely by opening the box. Mathematically, the cat is entangled with the lethal device and is in a superposition of dead and alive states. Schrodinger meant to highlight the absurdity of this interpretation – according to everyday intuitions, the cat is either alive or dead, but not both. MWI handles the situation in a slightly different way – according to MWI, the device was split into two states. In one world, the device releases the cyanide and the cat is alive, and in the other world, the device does *not* release the cyanide and the cat is alive. The cat itself was also split into two worlds, both of which are real (the cat that is alive occupies a different world from the cat that is dead). However, the observer exists in *both* worlds and only transfers the split to herself when the box is opened. MWI thus avoids the paradox. It is important to note that all the splits are actual physical processes governed by precise laws.

There are of course many issues with MWI that haven't been mentioned (such as issues with probability), as well as some other attractive features (the preservation of local interactions).

And while some aspects of MWI come across as counterintuitive or even absurd, the purpose here is to mention some of its fundamental ideas in order to understand the content of Deutsch's experiments. For an extensive treatment of MWI, see Vaidman (2002).

Part III – Objective Collapse theories

Objective collapse theories deal with the measurement problem by positing that wave functions naturally and stochastically collapse. There are generally two approaches – the first treats the collapse as originating from the wave function *itself*, while the second models the collapse as an *external* process. Collapse from "within" models modify wave equations by introducing non-linear terms, and are considered the most promising of collapse theories (Ghirardi-Rimini-Weber (GRW) theory is one well known example). Originally these models treated collapse simply as a function of individual particles, while more contemporary models tie frequency of collapse as a function of particle mass (referred to as the mass density ontology). The key advantage is that the wave functions of individual particles can behave like linear superpositions – as in traditional quantum mechanics – with a very low probability of collapsing. However, in a large *ensemble* of particles, if the wave function of a single particle in the ensemble collapses, the wave function of the entire *ensemble* collapses. So if the frequency of spontaneous collapse for a single particle is, say $f = 10^{-16}\ s^{-1}$, the frequency of spontaneous collapse for a system that consists of 10^{23} particles is $f = 10^{7}\ s^{-1}$. Thus microscopic particles can still be in linear superpositions, while macroscopic objects cannot (i.e. with very high probability). In objective collapse theories, the observer does not have any special status. Similar to the Copenhagen interpretation, *objective collapse theories treat individual particles as radically non-classical*. However, unlike the Copenhagen interpretation, there is a clear trigger mechanism for wave function collapse that puts macroscopic objects back in the realm of classical physics (see Ghirardi (2002) and Bacciagaluppi (2003) for an extensive treatment of collapse theories).

While objective collapse theories might seem ad hoc – in that they posit new fundamental processes – they are for the most part coherent and not particularly counterintuitive. Most importantly, they are experimentally verifiable. All researchers need to do is create large entangled ensembles and check how long it takes for them to collapse!

Part IV - Quantum Computing

A quantum computer is a device that performs operations on units of data called qubits by manipulating quantum-mechanical phenomena mentioned above, such as superposition and entanglement. While a classical bit can be in either the 0 state or the 1 state, a qubit can be in a superposition of the 0 and 1 states. Mathematically, a qubit is represented by the wave function:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad \text{(IV.1)}$$

The implications are quite powerful – instead of manipulating two values, quantum computers can manipulate an entire range of values. The catch, of course, is that quantum computers aren't exempt from the measurement problem. When the qubit $|\psi\rangle$ is *measured*, the wave function is collapsed into either the $|0\rangle$ or $|1\rangle$ state with respective probabilities of $|\alpha|^2$ and $|\beta|^2$ as dictated by the familiar Born Rule. As expected, the values of α and β can be determined by repeating the qubit manipulation and measurement a statistically significant number of times.

The interpretation of a computation therefore depends on the associated probabilities of the outcomes.

Quantum computers are made up of quantum circuits, which in turn consist of quantum logic gates. Quantum gates map *q* input qubits onto *q* output qubits (by doing a unitary transformation).[1] There is reason to believe that quantum computers will be able to solve certain problems much more quickly than classical computers. One promising algorithm is Shor's algorithm, which deals with integer factorization. Shor's algorithm has already been implemented on a very small number of qubits. It is also widely believed that quantum computers will be able to better simulate quantum behavior in certain physical systems than classical computers.

One important requirement is that quantum systems are isolated from the environment; that they are called *closed* systems. The mathematical formalism requires that state transformations of closed quantum systems are unitary, and that linear superpositions are maintained during the evolution of closed systems. The mathematics also require that all the qubits of the closed system evolve *simultaneously*. This is one of Deutsch's motivations for setting up experiment 2.

The small successes in quantum computing have also raised questions about what is *actually* going on when a qubit in a linear superposition is being manipulated. Hagar (2006) writes:

> *"Theoretical as it may seem, the question 'what is quantum in quantum computing?' has an enormous practical consequence ... It is almost certain that one of the reasons for this scarcity of quantum algorithms is related to the lack of our understanding of what makes a quantum computer quantum."*

This is just the question that Deutsch asks in experiment 2; his argument, of course, is that MWI is the only theory capable of giving a reasonable description of the manipulation process.

Part V – The Three Experiments

David Deutsch was one of the first physicists to claim that certain experiments involving quantum computers might favor MWI above all other interpretational theories. These experiments are featured in his essay "Three connections between Everett's Interpretation and Experiment" (Deutsch, 1986). Admittedly, what he calls 'experiments' are really *gedanken experiments* in the sense that they explore the potential consequences of particular assumptions, but may or may not be possible to implement. Throughout his discussion he vehemently attacks "non-MWI" theories, but he does little to elaborate on what exactly he means by "non-MWI." If he is simply referring to the Copenhagen interpretation, it would seem odd to not mention the Copenhagen interpretation explicitly, as he does in Deutsch (1985). In addition, there is a general consensus among both physicists and philosophers that the Copenhagen interpretation fails to specify precisely where collapse occurs and is therefore an imprecise theory. It is likely that he

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[1] There are a number of one-qubit gates – for example the identity gate "I" leaves a qubit unchanged, and the NOT gate "X" transposes the components of an input qubit. The Hadamard gate "H" is also a one-qubit gate with the following transformations:

$$|0\rangle \rightarrow [1/\sqrt{2}](|0\rangle + |1\rangle)$$
$$|1\rangle \rightarrow [1/\sqrt{2}](|0\rangle - |1\rangle)$$

The three-qubit Fredkin gate "F" has three inputs (including one or two control inputs) and three outputs. The F gate is reversible and can simulate the AND and NOT gates. The H and F gates feature in Deutsch's experiment 2.

includes Bohmian mechanics and objective collapse theories in his "non-MWI" category. Is it problematic, then that he doesn't address the very objects of his criticism in any detail? As a way of evaluating his *gedanken* experiments – and the conclusions he draws – I decided to explicitly treat his "non-MWI" theories as the Copenhagen interpretation and the objective collapse theories (alas, not Bohmian mechanics).

The general purpose of Deutsch's essay is to counter the widely held belief that MWI is simply an *interpretation* of the mathematical formalism of quantum mechanics with no experimental implications. The hope is that MWI is a *theory* that actually has experimental implications. He begins by asserting that all non-MWI theories attempt to modify the mathematical formalism of quantum mechanics by implicitly making the following (intuitive) assumption:

'Superpositions of distinct states of consciousness <u>do not</u> occur in nature.' (V.1)

This, of course, is certainly true for the Copenhagen interpretation, as it follows from the assumption that superpositions of macroscopic objects do not exist in nature, and the idea that measurement causes a collapse of the wave function. Similarly for objective collapse theories, (V.1) follows from the fact that the brain is a large ensemble of particles, and large ensembles are statistically very unlikely to be in superpositions of distinct states.

According to MWI, however, superpositions of distinct states of consciousness <u>do</u> occur in nature. This follows from the assumption that the universal wave function is a superposition of an extraordinarily large set of real, existing worlds. Past distinct states of consciousness as well as current distinct states of consciousness are subsystems of these superpositioned worlds, and are therefore superpositions as well (even though they might be in separate branches). While this comes across as a purely rhetorical and interpretational feature of MWI, Deutsch claims that (V.1) can be experimentally verified, and he proposes three experiments to do just that.

<u>Experiment 1</u> – Let $|\Psi_{\text{universe}}\rangle$ be the Heisenberg representation of the universal wave function. Since it is constant in time, it can be represented as:

$$|\Psi_{\text{universe}}\rangle = \int dt\, c(t)\,|t\rangle\,|\lambda(t)\rangle \quad \text{(V.2)}$$

where $|t\rangle|\lambda(t)\rangle$ is the simultaneous eigenstate of physical time observable $\mathbf{t}$ and a suitable observable $\boldsymbol{\lambda}(\mathbf{t})$ representing a "classical history" of the universe ($|t\rangle$ and $|\lambda(t)\rangle$ are non-separable subsystems – see Deutsch (1985) for a justification of this formalism). When you note that you are conscious, say at t_1, your observation is part of the classical history of the universe and can be written as

$$|\lambda(t_1)\rangle = \text{“I am conscious, observing } t_1\text{”} \quad \text{(V.3)}$$

At a second time t_2, you are presumably in a second conscious state:

$$|\lambda(t_2)\rangle = \text{“I am conscious, observing } t_2\text{”} \quad \text{(V.4)}$$

Equation (V.2) can now be written as:

$$|\Psi_{\text{universe}}\rangle = \int dt\, c(t_1)\,|t_1\rangle\,|\lambda(t_1)\rangle + \int dt\, c(t_2)\,|t_2\rangle\,|\lambda(t_2)\rangle \quad \text{(V.5)}$$

> for the range of $t_1 - \Delta < t < t_1 + \Delta$, $t_2 - \Delta < t < t_2 + \Delta$. This represents a superposition of quantum states. Therefore distinct states of consciousness *do* occur in nature.

Despite the mathematical formalism, it is clear that this is simply an example of how the MWI paradigm can be manipulated to make such counterintuitive statements as 'distinct states of consciousness *do* occur in nature.' A MWI detractor might call this a meaningless rhetorical maneuver – Deutsch himself admits that this first experiment is really "a trick." One reason he uses it as his first experiment, though, is to underscore the fact that non-MWI theories are somewhat awkward to express in the Heisenberg formulation of the wave function.[2] He writes: "…all it shows is that conventional (non-Everett) 'interpretations' are very awkward indeed to express in the Heisenberg picture" (p. 224). But is this something that we should be worried about? Since the Schrodinger and Heisenberg formulations are unitarily equivalent, this does not seem to be a pressing issue.

The first question to ask is why the Heisenberg representation is so important. Deutsch (1985 p. 4) argues that it is more natural for both general relativity and quantum field theory. But while this might be the case, it also seems to imply that the Schrödinger representation is *awkward* (interpretation wise) for general relativity and quantum field theory! Clearly the claim that the Heisenberg representation is somehow better than the Schrödinger representation implies that the Heisenberg representation is somehow more *philosophically fundamental* (despite the fact that they are unitary transforms of one another). This in turn is because MWI *requires* that the entire universe be described by a universal wave function. And since the Schrödinger representation privileges time above all other variables, but MWI does *not*, the Heisenberg representation is more philosophically (and mathematically) fundamental. But this seems to be begging the question.

Even more implicit to this entire discussion is the matter of universality. So the second question to ask is – how does universality come into the picture? MWI applies the entire mathematical apparatus of quantum mechanics to the universe, whereas both the Copenhagen interpretation and objective collapse theories are essentially limited to the microscopic domain. And while modeling the universe with quantum mechanical tools is *possible* with the Copenhagen interpretation and objective collapse theories – $|\Psi_{\text{universe}}\rangle$ is just a single, collapsed state – it isn't particularly *useful* or *insightful*. So while the Heisenberg representation might be awkward for non-MWI theories with regards to $|\Psi_{\text{universe}}\rangle$, so is the Schrödinger representation, and so is the entire mathematical apparatus of quantum mechanics, for that matter.

So what it boils down to whether the mathematics of linear superposition in quantum mechanics can be applied to the universe – *and this is not to be taken for granted*. For example, quantum cosmology is a field of study that investigates the consequences of applying quantum

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[2] At this point it is important to mention that there are two main ways of representing the wave function, the Schrödinger representation and the Heisenberg representation. According to the Schrödinger representation, *operators are constant* and the *wave function develops over time*. According to the Heisenberg representation, *operators (observables and others) have a time dependency*, but the *state vectors are time-independent*, and have an arbitrary fixed basis. The two pictures only differ by a basis change in Hilbert space (with respect to time-dependency), and are therefore unitarily equivalent. While the Schrödinger representation is more commonly used in traditional quantum mechanics, the Heisenberg representation is more natural to general relativity and field theories, which is one of the reasons that Deutsch mentions in experiment 1. Most of what has been discussed so far assumes the Schrödinger representation.

mechanics on the formation of the universe. Despite many attempts to pair quantum mechanics with general relativity, such as the Wheeler-deWitt equation, the field is mostly speculative. So non-MWI theories don't necessarily have to be theories that apply to the entire universe in order to be serious contenders – they just have to resolve issues in the traditional domain of quantum mechanics, i.e. the microscopic domain. It is therefore not unquestionably beneficial for the measurement problem to be resolved by a quantum theory that also makes novel claims about the universe. And it seems that the discussion has devolved into just the "theoretical [philosophical] arguments pro and contra" that Deutsch promised to avoid.

His final passage dealing with experiment 1 seems to confirm this:

> "*...we have in performing experiment 1 used successfully a formulation of quantum theory in which different states of consciousness do coexist in the state vector, and we have had no trouble in explaining our experimental observations in terms of it. We are so used to the phenomenon of 'time passing' that we do not normally regard it as an indictment of the whole of physics that all values of t occur on an equal footing, that the different instants they refer to are all equally real, but that 'we are only aware of one of them' (at a time!).*" (p. 224)

Suddenly Deutsch confesses that the purpose of experiment 1 is to explain how MWI matches our everyday experiences while also claiming that states of consciousness are in superposition. In the end, experiment 1 isn't an experiment at all – it is a clarification of a particular aspect of MWI that features in experiment 3 (as we shall soon see). And while it is certainly *interesting*, it is not the irrefutable "experimental implication" I was looking for.

The second experiment is lengthier and somewhat more promising. It is also the first time that Deutsch explicitly deals with quantum computing algorithms. The first part of the argument introduces the concept of quantum parallelism (which was quite novel in 1985/6), while the second part implements quantum parallelism to solve a simple problem (now known as "Deutsch's Problem") more efficiently than any known classical algorithm. He then raises the question of interpretation.

Before delving into experiment 2, it is important to clarify what quantum parallelism exactly is. Assume that a classical circuit can compute the values of the function $f(x)$ for a given input x in a single time step T. If x is a binary string of length n, one could compute the value of $f(x)$ for the 2^n possible values of the argument x in two ways – either by using a single copy of the circuit repeatedly for 2^n time steps (2^nT) with different input values of x at each step, or by using 2^n copies of the circuit, each with different input values of x, and obtaining all the values in a single time step T. *Quantum circuits can compute the values of the function f(x) for all possible values of the input x in a single time step and with a single copy of the circuit.* The first part of experiment 2 shows this explicitly.

> <u>Experiment 2: Quantum Parallelism</u> – We are interested in constructing a circuit whose input is x and whose output is $f(x)$ with probability 1, while also computing $f(x)$ more efficiently than a classical circuit. A single qubit $|x\rangle$ has two possible values, $|0\rangle$ and $|1\rangle$. The possible values of the *function* are $|f(x)\rangle = |0\rangle$ or $|f(x)\rangle = |1\rangle$. The Fredkin gate transforms two qubits in the following way:

$$|x\rangle\,|y\rangle \rightarrow |x\rangle\,|y \oplus f(x)\rangle \qquad \text{(V.5)}$$

Where $|x\rangle\,|y\rangle$ is a suitable input observable, and $|x\rangle\,|y \oplus f(x)\rangle$ is a suitable output observable. Note that the third input $f(x)$ is hardwired into the circuit (this is one of the properties of Fredkin gates). If the second qubit is set to $|y\rangle = |0\rangle$, then the transformation carried out by the Fredkin gate is:

$$|x\rangle\,|0\rangle \rightarrow |x\rangle\,|0 \oplus f(x)\rangle \qquad \text{(V.6)}$$

Where $\oplus$ is addition mod 2. This transformation (V.6) is therefore equivalent to:

$$|x\rangle\,|0\rangle \rightarrow |x\rangle\,|f(x)\rangle \qquad \text{(V.7)}$$

Note that we have just obtained $|f(x)\rangle$ from $|x\rangle$. Also note that nothing particularly exciting has happened yet – (V.7) takes x and spits out $f(x)$, just like any classical circuit might.
However, things change when $|x\rangle$ is in a superposition of two output qubits:[3]

$$|x\rangle = [1/\surd 2](|0\rangle + |1\rangle) \qquad \text{(V.8)}$$

This means that $|f(x)\rangle$ has the following value:

$$f\{\,[1/\surd 2](|0\rangle + |1\rangle)\,\} = [1/\surd 2](|f(0)\rangle + |f(1)\rangle) \qquad \text{(V.9)}$$

Already we can see that the Fredkin gate will process information about both $|f(0)\rangle$ and $|f(1)\rangle$! Mathematically (V.7) turns into:

$$|x\rangle\,|0\rangle \rightarrow |x\rangle\,|f(x)\rangle \qquad \text{(V.7)}$$

$$[1/\surd 2](|0\rangle + |1\rangle)\;|0\rangle \rightarrow [1/2](|0\rangle + |1\rangle)\,(|f(0)\rangle + |f(1)\rangle) \quad \text{(V.10)}$$

$$[1/2](|0\rangle\,|f(0)\rangle + |1\rangle\,|f(0)\rangle + |0\rangle\,|f(1)\rangle + |1\rangle\,|f(1)\rangle) \qquad \text{(V.11)}$$

The output therefore contains information both about $|f(0)\rangle$ and $|f(1)\rangle$. *This* is quantum parallelism, and it can mathematically be extended to n qubits (see Marinescu (2005, pp.205-206) for a simple proof). Thus quantum parallelism allows us to construct the entire truth table of a quantum gate array with 2^n entries in a single time step!
The trouble, of course, is that when we *measure* the output, we can only observe *one value* of (V.11) i.e. one value of the truth table. So in order to actually *exploit* quantum parallelism, clever

[3] This can be prepared using a Hadamard gate with transformation (IV.2)

algorithms need to manipulate the probabilities associated with each value. "Deutsch's Problem" is one such algorithm.

Experiment 2: "Deutsch's Problem" – Let's say that a programmer is interested in calculating $f(0) \oplus f(1)$ instead of just $f(x)$. By modular arithmetic:

$$0 \oplus 0 = 0,\ 0 \oplus 1 = 1,\ 1 \oplus 0 = 1,\ 1 \oplus 1 = 0 \quad \text{(V.12)}$$

So if $f(0) = f(1)$, then $f(0) \oplus f(1) = 0$, and if $f(0) \neq f(1)$, then $f(0) \oplus f(1) = 1$. Classically, calculating $f(0) \oplus f(1)$ requires calculating both $f(0)$ and $f(1)$ with a total time of 2T. *A quantum algorithm can reduce that time to T*. All we need to do is create the state:

$$[1/\sqrt{2}](|0\rangle\,|f(0)\rangle + |1\rangle\,|f(1)\rangle) \qquad \text{(V.13)}$$

And find the inner product (this is simple but tedious – see Appendix) with a new output observable in the following non-degenerate basis:

$$|zero\rangle = |0\rangle\,|0\rangle - |0\rangle\,|1\rangle + |1\rangle\,|0\rangle - |1\rangle\,|1\rangle \text{ (V.14)}$$

$$|one\rangle = |0\rangle\,|0\rangle - |0\rangle\,|1\rangle - |1\rangle\,|0\rangle + |1\rangle\,|1\rangle \text{ (V.15)}$$

$$|fail\rangle = |0\rangle\,|0\rangle + |0\rangle\,|1\rangle + |1\rangle\,|0\rangle + |1\rangle\,|1\rangle \text{ (V.16)}$$

$$|error\rangle = |0\rangle\,|0\rangle + |0\rangle\,|1\rangle - |1\rangle\,|0\rangle - |1\rangle\,|1\rangle \text{ (V.17)}$$

(each pair on the RHS has a normalization coefficient of ½). The surprising result is that if the observed value is $|zero\rangle$, then it *must be the case* that $f(0) = f(1)$, and if the observed value is $|one\rangle$, then it *must be the case* that $f(0) \neq f(1)$. The probability of measuring *a value* for $f(0) \oplus f(1)$ (either $|zero\rangle$ or $|one\rangle$) is ½, and the probability of *not* measuring a value (i.e. $|fail\rangle$) is also ½. Thus the quantum algorithm computes $f(0) \oplus f(1)$ in a single step.[4]

The point of experiment 2 is to show that MWI is the only realistic interpretation of quantum parallel processing. *So how exactly does MWI describe what is going on?* Deutsch explains that according to MWI, two algorithms (one for $f(0)$ and another for $f(1)$) are simultaneously executed by different instances of the same processor in distinct Everett branches. The observer then "transfers information depending on the whole graph of f into a single branch," and erases all information from the other branch (Deutsch, 1986 p. 219).

Deutsch then asserts that all non-MWI theories cannot explain the processes internal to a quantum circuits as an objective sequence of phenomena. He doesn't claim that when quantum

[4] It is worth studying Marinescu (2005, pp. 207-209) for a more rigorous and detailed solution (Deutsch's Problem is solved with two Hadamard gates, a Fredkind gate, and a final Hadamard gate).

parallelism is achieved experimentally the conventional interpretation will be refuted empirically. Rather, the conventional interpretation will be useless while the MWI explanation will be insightful and intuitive. When a complex algorithm with multiple parallel branches is being calculated, where are the calculations being done? If there is a bug in the "code" of one of the parallel branches, then the entire computation will not work. If all the parallel branches don't exist in reality, how can a bug in *one* of the branches supervene on the entire computational process?

The Copenhagen interpretation of course fails to provide much comfort – nothing can be said about what functionally happens between the preparation of the input and the observation of the output. For complicated and lengthy circuits, all the steps can be represented mathematically, but one cannot say that they *actually occurred*. The only thing that *occurred* was the overall computation. Objective collapse theories don't provide much comfort either, as they focus on resolving the microscopic/macroscopic divide. An objective collapse mechanism doesn't describe what actually occurs on the microscopic scale. In this respect objective collapse theories are similar to the Copenhagen interpretation.

Is there any way for non-MWI theories to interpret quantum parallel processing? If we claim that we are dealing with new fundamental rules for microscopic particles, the mathematics say that a particle can partially be in two states simultaneously, so at the microscopic level, the particles *is* partially in two states simultaneously. This might seem rhetorical, but it depends on how seriously one wants to take the mathematics. If there is a clear theory that explains where to make the macro/micro cut – as in objective collapse theories – then this kind of description could seem to work. Instead of claiming that there are many worlds, one might claim that physics fundamentally changes at the microscopic scale. But this once again seems to have more of a philosophical nature than an experimental nature, that is decided based on personal philosophical leanings more than on hard data.

Deutsch also admits that experiment 2 is a glorified two-slit experiment.[5] In the two-slit experiment, a single photon hits two slits to form an interfering wave pattern on a distant screen. According to the Copenhagen interpretation, it is undesirable to say whether the particle went through one slit or the other or both, and nothing can be said about the *process* other than the mathematical description. According to MWI, the photon simultaneously goes through both slits in parallel worlds. The insight that Deutsch is trying to convey with quantum parallelism is that it is impossible to avoid wondering what is physically going on when algorithms involve many steps and calculation times are lengthy.

Ultimately, however, the Copenhagen interpretation and objective collapse theories predict the same experimental results as MWI, but have different conceptual frameworks. Whether they are more or less desirable frameworks is more a philosophical question than an experimental one. Deutsch's second experiment therefore feels slightly underwhelming.[6]

We finally move on to experiment 3, explores the nuances of quantum collapse in the Copenhagen interpretation. According to Deutsch, it is crucial for MWI to determine experimentally whether or not the superposition principle holds for states of distinct consciousness. In MWI, the same dynamical rules apply to all physical systems, including

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5 At this point I began to question whether all the time I spent studying the nitty gritty details of quantum parallelism was worthwhile.

6 Armond Duwell has a more lofty critique of experiment 2 and argues that any other interpretation that treats the state vector as representing real ontological features of a system can explain quantum speed up as well; see Duwell (2007).

conscious systems, whereas according to the Copenhagen interpretation, conscious systems have a privileged status. Deutsch's experiment 3 consists of three two-state systems and one quantum computer with an 'artificial intelligence' program, which plays the dual role of observer and observed object.

Experiment 3: Quantum Artificial Intelligence – Subsystem 1 is a silver atom in the state: $|\rightarrow\rangle = [1/\sqrt{2}](|\downarrow\rangle + |\uparrow\rangle)$. Subsystems 2 and 3 are the "sense organ" for the quantum observer. They are prepared in a receptive state $|\downarrow\rangle|\downarrow\rangle$.

Step 1 – The silver atom passes through the apparatus. If the $|\uparrow\rangle$ component of the silver atom passes close to system 2, the state of system 2 is flipped to $|\downarrow\rangle|\uparrow\rangle$, and if the $|\downarrow\rangle$ component of the silver atom passes close to system 3, the state of system 3 is flipped to $|\uparrow\rangle|\downarrow\rangle$

Step 2 – Subsystem 4, the quantum observer, examines subsystems 2 and 3 and can tell whether the sense organ recorded spin up, spin down, or whether it is in the ready state. The observer's experience can be rephrased in terms of **P** and **Q**, two observables (if **Q** = 1 and **P** = 1, then the particle had spin $|\uparrow\rangle$ and if **Q** = –1 and **P** =1, the particle had spin $|\downarrow\rangle$). At this point, according to MWI the state of the observer is a superposition of **Q** = 1 and **P** = 1 and **Q** = –1 and **P** = 1, while according to the Copenhagen interpretation, the wave function of the silver atom has been *collapsed.*

Step 3 – Having experienced this "state of consciousness," the quantum observer makes a public record of whether it has observed a definite spin value or not without revealing what exactly it learned.

Step 4 – The next step is to undo, by reversing the dynamical evolution, Steps 2 and 1. This is in principle possible, because *"the steps involve only the quantum computer which can effect any desired unitary transformation upon the state of a subsystem of itself"* (p. 223)

Step 5 – Finally the horizontal component of the spin of the silver atom is measured

Any interpretation that involves the collapse of the wave function should measure $|\rightarrow\rangle$ or $|\leftarrow\rangle$ with equal probability, while MWI should invariably measure $|\rightarrow\rangle$. This is because, according to non-MWI theories, a collapse occurred when the observer *viewed* the result without revealing what exactly it observed at Step 2. Once it collapsed to either $|\uparrow\rangle$ or $|\downarrow\rangle$, all information about the original wave function superposition was lost. According to MWI, however, the final state of the observer at Step 3 (i.e. before reversing the process) is a *superposition* of states! Deutsch writes that the quantum computer "experiences the splitting and reemergin of its own consciousness by observing physical evidence for which there is no alternative realistic interpretation" (p. 225).

Deutsch's third experiment is really a critique of the Copenhagen interpretation, namely the lack of definition of measurement and the mystery of the wave collapse. According to the

Copenhagen interpretation, Deutsch's artificially intelligent quantum computer would probably count as a macroscopic observer, although as mentioned many times already, the Copenhagen interpretation does not give a precise description of when exactly collapse occurs. This is a known issue in the Copenhagen interpretation, and one of the primary reasons that so many physicists and philosophers don't see it as the "final word." But did we need this *gedanken experiment* to point this out?

Granted Experiment 3 would be a definitive test of the Copenhagen interpretation, which is a theory riddled with issues. But would it *prove* MWI? Objective collapse theories treat the issue in an entirely different manner. If the quantum computer is large enough, then it will collapse and the resulting measurement will be $|\rightarrow\rangle$ or $|\leftarrow\rangle$. If the quantum computer is small enough to have a low chance of collapsing, objective collapse theories predict the same results as MWI. So the deciding factor is the associated parameter of the quantum computer, something that is (theoretically) testable without "quantum artificial intelligence" or complicated manipulations.

One might also wonder whether he is begging the question by assuming that an artificially intelligent quantum computer could be built. Would the Copenhagen interpretation even allow for a large, artificially intelligent quantum computer?

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Although thought provoking, his three experiments are somewhat underwhelming. Experiment 1 is a rhetorical exercise, while experiment 2 is interesting to think about but hardly an experiment. Finally, experiment 3 *does* deal decidedly with the Copenhagen interpretation, but not in a particularly elegant or necessary way. For Deutsch to claim that his three experiments should dispel any doubts about MWI is a form of sensationalism. I spent all this time trying to understand what he says, and after all this research and writing I am a little disappointed. I must also confess that I am secretly relieved that MWI isn't the incontrovertible theory of the universe.

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For my physics friends – When someone "*begs the question*," they are using circular reasoning by assuming the conclusion of an argument.