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The Coming of the Quantum Cats

Quantum physics is the set of laws that govern the behaviour of things on small scales – essentially, the size of atoms and smaller. To put that scale in perspective, it would take roughly ten million atoms lined up side by side to stretch across the gap between two of the points in the serrated edge of a postage stamp. At one level, it is not surprising that the laws of physics that operate at such small scales are different from the laws that operate on a human scale, which were discovered by Isaac Newton in the seventeenth century. Newtonian physics describes the behaviour of things like billiard balls rolling across a table and colliding with one another, waves rippling across the surface of a pond, or the launch of a rocket ship on its way to Mars. But at another level, it is utterly astonishing that quantum physics turns out to be dramatically different from Newtonian physics – different in its very nature, not just in minor ways. Because, after all, things like billiard balls, water in a pond, and rocket ships are all made of atoms. How can the whole behave so differently from the sum of its parts?

There is no single satisfactory answer to that question. There are several possible answers, all equally valid, which is an unsatisfactory situation in itself. And none of those answers 'make sense' in terms of our everyday experience of the world. This is the single most important thing to take on board concerning quantum physics. It is totally outside our everyday experience. There is no way that the human mind can understand what quantum entities such as light or electrons 'really are'. All we can do is carry out experiments, and interpret the results of those experiments by making analogies with things we think we understand in the everyday world.

NEITHER WAVE NOR PARTICLE

In some experiments, the behaviour of light seems to be like the behaviour of ripples on a pond; in other experiments, it seems to be like a stream of tiny billiard balls. But this does not mean that light 'is' a wave or 'is' a particle, nor even that it is a mixture of wave and particle. It is something we cannot envisage, which if asked one question will respond like a wave, while if asked another question will respond like a particle. The same is true of electrons and all other quantum entities. Perhaps, limited by our human experience, we are asking the wrong questions. But we are stuck with the questions and answers we've got.

As long ago as 1929, the physicist Arthur Eddington summed the situation up, in his book *The Nature of the Physical World*. 'No familiar concepts can be woven around the electron,' he wrote; 'something unknown is doing we don't know what.' And he points out that 'I have read something like it elsewhere –

The slithy toves
Did gyre and gimbal in the wabe'*

In this regard, nothing has changed in the past eighty years. We still don't know what electrons (or other quantum entities) are, nor how they do the things they do.

Indeed, by breaking our mental link with things like waves and particles, it might be more helpful to translate all of quantum physics into the language of 'Jabberwocky'; it would certainly make just as much sense. Which makes it all the more remarkable that without knowing what quantum entities are or how they do the things they do, by knowing that they do do certain things when prodded in certain ways physicists are able to use quantum entities. This is a bit like the way you can learn to drive a car by learning how to manipulate the controls, without having the faintest idea what is going on under the bonnet.

To take just two examples, quantum physics is essential for the

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* Eddington is quoting from Lewis Carroll's *Jabberwocky*.

design of computer chips, which are in everything from your mobile phone to supercomputers used in weather forecasting, and quantum physics explains how large molecules like DNA and RNA, the molecules of life, work. Studying quantum physics is not just an esoteric hobby for unworldly boffins: it has direct, practical benefits. In this book, however, I am more concerned (except in part of Chapter Three) with the esoteric and, if you like, philosophical implications of quantum theory. And nothing could be stranger than the story of Schrödinger's cat and her successors. But before we meet the felines, there are some basics of quantum physics to come to terms with.

It's a sign of how inadequate our everyday experiences are as a guide to the quantum world that, having cautioned you that quantum entities are neither waves, nor particles, nor a mixture of wave and particle, the best way to begin to get some insight into what goes on at the sub-atomic level is to consider the ways in which such entities behave *like* waves or particles. This provides at least some insight into one of the most important, but also non-commonsensical, features of the quantum world – uncertainty.

A QUANTUM OF UNCERTAINTY

In quantum physics, uncertainty is a precise thing. For a quantum entity, there are pairs of parameters, known as conjugate variables, for which it is impossible to have a precisely determined value of each member of the pair at the same time. The more accurately you know property A, the less accurately you know property B, and vice versa. This is not the fault of our inadequate measuring equipment. It is a law of nature, discovered by the physicist Werner Heisenberg in 1927, and known as Heisenberg's Uncertainty Principle. The most important of these pairs of conjugate variables are position/momentum, and energy/time.

The position/momentum relationship is the archetypal example described by Heisenberg. Momentum, in this context, is equivalent to velocity, and velocity describes both the speed and direction that something is moving in. Heisenberg found that the uncertainty in the position of an entity such as an electron, multiplied by the uncertainty in its momentum, is always bigger than a certain (tiny!) number, Planck's constant, divided by 2π. In principle, you can get as near to this limit as you like. But the more precisely the position of, say, an electron is pinned down, the more uncertainty there is about where the electron is going. The more accurately its momentum (or velocity) is determined, the less accurately is its position defined. This uncertainty is a property of the electron (or other quantum entity) itself. An electron itself does not 'know' both where it is and where it is going at the same time.

This is where the wave and particle analogies are useful. But remember that they are only analogies. A wave is a spread out thing. It might well be travelling in a definite direction at a definite speed, but it cannot be located at a point. A particle, if it is small enough, can very nearly be located at a point, provided that it is not moving with a well-defined momentum. But if it moves – if it has a certain momentum – it is no longer located at a point. The more a quantum entity is constrained by circumstances to act like a wave, the less certain it is where the entity is located. The more it is constrained to act like a particle, the less certainty there is about where it is going.

The standard way to describe this is in terms of probabilities. If an electron is fired off from an electron gun in the direction of a phosphorescent screen, as in an old-fashioned TV cathode ray tube, the moment the electron leaves the gun the wave representing it begins to spread out through space, because its position is uncertain. In principle, the laws of quantum physics tell us, the electron could end up anywhere in the Universe; but there is a very high probability that it will strike the screen and make a spot of light there. The instant it does so, the uncertainty in its position shrinks dramatically to the size of the spot on the TV screen. This is called the collapse of the wave function. Then, the wave begins to spread out again from the new location. Unless the electron has got tied up in an atom, or trapped in some other way, its position becomes more and more uncertain as time passes. If it has got tied up in an atom, it is still constrained by quantum uncertainty; but that is not directly relevant to the search for the Multiverse.

THE ONLY MYSTERY

All this is hard to get your head round. But the essence of the quantum world can be summed up in terms of one simple experiment, involving sending light, or a beam of electrons, through two holes in a blank obstruction. Richard Feynman, who won a Nobel Prize for his work on quantum theory, said that this experiment 'has in it the heart of quantum mechanics. In reality, it contains the *only* mystery.'* And if you find you still have trouble getting your head round what is going on in the experiment with two holes, he also commented: 'I think I can safely say that nobody understands quantum mechanics . . . Nobody knows how it can be like that.'† So you are in good company.

The experiment with two holes is also called the double-slit experiment, because when it is carried out using light the holes can simply be two parallel slits made in a piece of card or paper with a razor. Light is shone through the two slits in a darkened room, and spreads out on the other side before arriving at a second sheet of card, where it makes a pattern. The pattern is one of alternating light and dark stripes. In the nineteenth century this was explained, or interpreted, as the result of waves spreading out from the two slits and interfering with one another, like overlapping ripples spreading out from two pebbles dropped into a still pond simultaneously. Where the waves are moving in step, they combine their strength to make a bright stripe; where the waves are moving out of step, they cancel each other and leave a dark stripe. This seemed to be definitive proof that light is a wave.

But at the beginning of the twentieth century Albert Einstein proved that light behaves like a stream of particles. In a process known as the photoelectric effect, light falling onto a metal surface knocks electrons out of the surface. The energy of the ejected electrons only has certain values, and Einstein interpreted this as the result of light arriving at the surface in the form of little particles, now called

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* Richard Feynman, Robert Leighton and Matthew Sands, *The Feynman Lectures on Physics Volume III*, Addison-Wesley, Massachusetts, 1965. The term 'quantum mechanics' is essentially synonymous with 'quantum physics'.

† *The Character of Physical Law*.

photons, each with a certain energy. It was, incidentally, for this work, not either of his theories of relativity, that Einstein received the Nobel Prize.

So there are two sorts of experiment you can do with light, one which shows light behaving as a wave and one which shows light behaving as a stream of particles. Exactly the same thing happened with the investigation of electrons, but the other way round.

Towards the end of the nineteenth century, experiments directed by J. J. Thomson in Cambridge proved to everyone's satisfaction that electrons are particles. But in the 1920s, experiments carried out by several researchers, including J. J.'s son, George, showed electrons behaving as waves. J. J. Thomson got the Nobel Prize for proving that electrons are particles; George Thomson got the Nobel Prize for proving that electrons are waves. Nothing better sums up the non-commonsensical nature of the quantum world.

Today, variations on the experiment with two holes are so subtle that they can be carried out by shooting single entities, photons or electrons in different experiments, through the holes one at a time. I'll describe the results for electrons, but exactly the same kind of experiments have been carried out for photons as well. Instead of a sheet of card on the other side of the experiment, there is a detector screen like a computer monitor which records a spot of light every time an electron arrives, and allows these spots to stay and build up into a pattern as more and more electrons arrive. When researchers do this, each electron arrives as a particle and makes a single spot of light on the screen. But as hundreds and thousands of electrons are fired through the experiment one after another, the pattern that builds up on the screen is an interference pattern, the typical pattern for waves moving through the experiment.

Each electron seems not only to go through both holes at once and interfere with itself, but then to find its place in the interference pattern alongside all the electrons that have gone before and all the electrons that are still to come. Entities in the quantum world seem to know about the whole experiment, both in terms of space (the two holes) and in terms of time.

There's more. The experimenters can set up detectors to look at the two holes, and monitor which one each electron goes through. When they do this, they never see the electron going through both holes at once. They see it go through one hole or the other. And when they do this, there is no interference pattern. The spots on the screen form two blobs, one behind each hole, just as you would expect if they were made by particles. The electrons also seem to know if they are being watched or not – and the same is true for photons and all other quantum entities.

This is why Feynman said that the experiment with two holes has in it the heart of quantum physics, and that nobody knows how it can be like that. We might, indeed, just as well talk of slithy toves gyring and gimballing in the wabe as of electrons going through the experiment with two holes – except for one thing. Even though we cannot *understand* what is going on in the quantum world, the equations of quantum mechanics make it possible to *describe* what is going on, with great precision. By knowing, for example, the circumstances in which electrons seem to move like waves and the circumstances in which they seem to behave like particles, we can design computer chips. It may be crazy, but it works.

INTERPRETING THE UNIMAGINABLE

So people try to come up with images of how it works in terms that human beings can comprehend. These are called interpretations of quantum physics. The first of these aids to the imagination to be developed is called the Copenhagen Interpretation, because it was largely developed by scientists working in that city. It was the standard way of thinking about the quantum world from the 1930s to the 1980s, and is still widely taught. But it raises at least as many questions as it answers.

According to the Copenhagen Interpretation, it is meaningless to ask what atoms, electrons and other quantum entities are doing when we are not looking at them. And we can never be certain what the precise outcome of a quantum experiment will be. All we can do is calculate the probability that a particular experiment will come up with a particular result. This is exactly like the way that if you roll a pair of true dice there will be a certain probability of getting a score of 12, another probability of getting a total of 5, and so on. You also know you will never get a total of 17, or 4.3. The same sort of thing happens in quantum experiments. Some outcomes are more likely, some are less likely, and some are impossible.

With dice, you may not know what total you will get in advance, but at least you know the dice are there even if you are not looking at them. When quantum entities are not being observed, the Copenhagen Interpretation says, they dissolve into a mixture of waves (sometimes called a wave function) representing the various probabilities. This mixture is called a superposition of states. When a measurement is made, the act of measuring forces the quantum entity to choose one of these states, in line with the various probabilities, and the wave function collapses. But as soon as the measurement has been made, the quantum entity once again begins to dissolve into a mixture, a new superposition of states.

Looking specifically at the experiment with two holes, the Copenhagen Interpretation says that as soon as the electron leaves the gun on one side of the experiment it dissolves into a superposition of states, waves that pass through both holes. Once the waves have gone through the holes, they interfere with one another to produce a new superposition of states. Then, when the superposition reaches the target screen the wave function collapses into a single point and the electron becomes a real particle, at least temporarily. But if we set the experiment up to see which hole the electron goes through, the act of observation forces the wave function to collapse at one of the holes, and it then spreads out on the other side from a single site, with no interference, creating a different kind of pattern.

The situation has been summed up neatly by Heinz Pagels, in his book *The Cosmic Code*. It is worth quoting his comments, since at the time he was President of the New York Academy of Sciences, and surely knew what he was talking about. He says that according to the Copenhagen Interpretation:

> There is no meaning to the objective existence of an electron at some point in space, for example at one of the two holes, independent of actual observation. The electron seems to spring into existence as a real object only when we observe it . . . reality is in part created by the observer.

You may think this is absurd. If so, you are in good company. Erwin Schrödinger, another physicist who received a Nobel Prize for his work in quantum physics, hated the Copenhagen Interpretation (he once said of the quantum theory he had helped to father, ‘I don’t like it, and I wish I’d never had anything to do with it’), and dreamed up his famous ‘cat in a box’ experiment to highlight its absurdity. This is purely an imaginary scenario – a ‘thought experiment’. No cat has ever suffered the indignities Schrödinger describes. But that doesn’t make it any less powerful as an indictment of the Copenhagen Interpretation.

Schrödinger’s own version of the parable involved radioactive atoms being monitored by sophisticated Geiger counters. My version is slightly different, and brings out an additional feature of the weirdness of the quantum world.

THE MOTHER OF ALL QUANTUM CATS

Imagine a box, perhaps about the size of a shoe box, that is completely empty except for a single electron. The Copenhagen Interpretation says that the wave function of the electron spreads out to fill the entire box, so that if we look inside there is an equal chance of finding the electron anywhere in the box. Now imagine sliding a smooth, upright partition exactly down the middle of the box, like the dividing partitions used by magicians in the illusion of sawing a lady in half. Common sense tells us that the electron must now be trapped in one half of the box – that would certainly be the case if it was a tiny ball bouncing around inside the box. But the Copenhagen Interpretation tells us that the wave function of the electron still fills both halves of the box. This corresponds to an equal probability of finding the electron on either side of the partition, if we take a look.

Now comes the additional feature. Imagine the box divided completely into two separate halves, as with the best sawing-the-lady-in-half illusions, so the two halves can be separated, with a gap between them. The Copenhagen Interpretation still says that the wave function of the electron fills both halves of the box equally. You could take one of the half-boxes on a trip to the Moon, or farther, and this would still be the case, even though the wave function did not exist in the gap between the boxes. The wave function only collapses to become an electron located at a point when you look inside one of the half-boxes. It doesn't matter which one. If you look in box A and see an electron, the wave function disappears from box B; if you look in box A and *don't* see an electron, the wave function disappears from box A and the electron is certain to be in box B. If you do see the electron, once you stop looking the wave function spreads out again, but only to fill the half-box where we now know the electron is located.

This aspect of quantum weirdness wasn't Schrödinger's main concern when he dreamed up his so-called 'cat paradox', published in 1935. He was highlighting another feature of quantum weirdness, the superposition of states. In my variation on the theme, go back to the stage where the shoe box has been divided into two, and there is a 50:50 chance of finding the electron on either side of the partition. Imagine that the box is in a large, sealed room, where a single cat lives in quiet comfort, with plenty to eat and drink. But the box is connected to a detector, which at some appointed time will make a measurement to see if the electron is in one particular half of the box. If there is no electron there, nothing happens. But if an electron is detected, what Schrödinger called a 'diabolical device' shatters a flask of poison, which floods the chamber and kills the cat.

Or does it? Common sense says that there is a 50:50 chance that the cat will survive, and a 50:50 chance that the cat will die. The Copenhagen Interpretation says that because no outside observer has seen what is going on, when the half-box is examined instead of the electron wave function collapsing the wave function of the whole room moves into a superposition of states, one corresponding to a live cat and one corresponding to a dead cat. In Schrödinger's words, 'the wave-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts.'* The cat is both dead and alive at the same time (or, if you prefer, neither dead nor alive) and stays that way until somebody opens the door to the room and looks inside.

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* Translation from Wheeler and Zurek.

Then, the wave function collapses – not at the moment the door is opened, but as if it had happened at the moment the automatic monitoring equipment looked inside the box, with all that that implies for the appearance of the possibly dead cat.

The weirdness doesn't end there. Other physicists were quick to point out that this could lead to an infinite regression. If you are the only person that looks inside the room, do you make the wave function collapse, or do you become part of the superposition of states? And if a friend phones you to ask about the outcome of the experiment, does the wave function collapse then, or does the friend become part of the superposition? Taken to its logical extreme, this line of argument raises the question, seriously debated by cosmologists, of who (or what) can observe the entire Universe and make its wave function collapse into a definite state. Why isn't everything hung up in a superposition of states?

If there was anything better than the Copenhagen Interpretation, it would have been discarded long ago. But there isn't anything better. There are only alternative interpretations,* which are precisely as good as the Copenhagen Interpretation, in the sense that they are just as good at predicting the outcomes of quantum experiments, but no better, because they do not predict anything the Copenhagen Interpretation does not predict. And they each involve inevitable components of quantum weirdness, such as signals that travel backwards in time or instantaneous communication between quantum entities across great distances. So which quantum interpretation you choose to work with is simply a preference based on which aspect of quantum weirdness you feel most comfortable (or least uncomfortable) with. The one that is relevant to the search for the Multiverse, and which is exactly as good as all the other interpretations, including the Copenhagen Interpretation, as far as any experimental test goes, is the Many Worlds Interpretation, developed by Hugh Everett in the 1950s.

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* Discussed in my book *Schrödinger's Kittens*.

THE MANY WORLDS OF HUGH EVERETT

Everett was born in Washington, DC, on 11 November 1930. He clearly had a precocious interest in the big question of life, the Universe and everything, since in his thirteenth year he wrote to Albert Einstein to ask what it is that holds the Universe together; in a letter dated 11 June 1943, Einstein replied that 'there is no such thing like an irresistible force and immovable body.'* After graduating from high school, Everett studied chemical engineering at the Catholic University of America and also in Washington, receiving his first degree in 1953. One of his friends at the University, Karen Kruse, later married the science-fiction writer Poul Anderson, who was himself a physicist and became an enthusiast for Everett's version of the Multiverse idea, which coloured several of his stories.

By the time he received his bachelor's degree, Everett's own interests had turned towards theoretical physics, but in order to take his education further he needed financial support. As an outstanding student, he was offered a prestigious National Science Foundation Fellowship to work for a PhD in mathematics at Princeton, which he was happy to accept. This was at the height of the Cold War, and the terms of the Fellowship required him to work on game theory, which in spite of its cosy name has important military applications. Everett did the work he was supposed to do, but as soon as he was safely installed at Princeton he also began looking for a way to transfer to the Physics Department. He made the transfer at the beginning of his second year at Princeton, in September 1954, and was initially assigned to the care of Frank Shoemaker as his thesis adviser. But although physics did become the subject of Everett's PhD work, he also continued his work on game theory.

Almost immediately after officially becoming a physicist, Everett came up with the big idea that he is now remembered for. Following a party at which a considerable amount of sherry was consumed,

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* Everett-related quotes are taken from an unpublished 'Biographical Sketch' by Eugene Shikhovtsev.

Everett, his fellow student Charles Misner (who would later become a leading expert on relativity theory) and a visitor, Aage Petersen, amused themselves by dreaming up increasingly ridiculous implications of quantum puzzles like the parable of Schrödinger's cat. Their choice of subject was thanks to the presence of Petersen, who was then working as an assistant to Niels Bohr, one of the quantum pioneers and the leading proponent of the Copenhagen Interpretation. The puzzles, like Schrödinger's cat, all stem from the difficulty of understanding and interpreting what happens when the wave function collapses. Everett's big idea, initially tossed out more or less as a joke, was to ask, what if the wave function doesn't collapse? What if the superposition of states stays forever?

In the cold light of the following day, the wild idea didn't seem so wild to him after all, and Everett decided to investigate it properly, using the equations of quantum theory. But first he had other duties – a lecture on military applications of game theory that he gave in December 1954, and the small matter of graduate examinations, which he took in the spring of 1955. He received his Master's degree after passing those exams. So it wasn't until the summer of 1955 that he began to write up his big idea and its implications in proper mathematical language. The result was a draft thesis, typed up by his girlfriend Nancy Gore, who Everett married the following year. The subject was outside the scope of Frank Shoemaker's expertise, so, armed with this material, Everett transferred from Shoemaker to John Wheeler as his thesis adviser – in fact, he had already discussed the idea with Wheeler before writing the draft dissertation.

Wheeler was the perfect man for the job. He was born in 1911, and in the mid-1930s, shortly after finishing his own PhD, he had worked with Niels Bohr in Copenhagen for a couple of years. Soon after returning to America he had been Richard Feynman's adviser when Feynman was a PhD student at Princeton. An expert on the general theory of relativity, he would be the person who coined the name 'black hole' in its modern astronomical context, in 1967. Wheeler was always open to new ideas, and happy to encourage their development even if he did not always agree with them.

At the beginning of his third year at Princeton, in September 1955, Everett wrote two short papers for Wheeler developing his idea; these are now in the archive of the Niels Bohr Library of the American Institute of Physics, along with other Everett documents. In one of these papers, Everett writes for the first time about the 'splitting' of an observer whenever a quantum measurement (such as looking in the shoe box for the electron) is made. Wheeler wrote in the margin, 'Split? Better words needed.' But Everett disagreed, and used the analogy of the division, or splitting, of an 'intelligent amoeba with a good memory', even though Wheeler was not keen on it. Today, it seems an almost ideal way to explain how Everett's version of quantum physics works.

On this picture, in a situation like the electron in the shoe box, after the partition is lowered, when an observer opens the lid on one side of the partition and looks inside there is no collapse of the wave function. Both outcomes are equally likely so both are equally real. The wave function does not collapse, but the entire Universe, including the observer, splits. In one branch of reality, there is an observer who sees an electron. In the other branch of reality, there is an observer, identical to the first observer up to that point, who does not see an electron. Amoebas reproduce by splitting in two. If there were an intelligent amoeba with a good memory, before the split there would be one individual, but after the split there would be two individuals with identical memories up to that point, who would then lead separate lives developing along different paths. The difference is that in the quantum case, it isn't so much that the Universe, or the observer, splits, but that the overall wave function, the superposition of states, has built in to itself a bifurcation at the moment in time where the measurement, or observation, is made. Everett's great achievement was to express this in accurate mathematical language, and to prove that his version of quantum physics is identical in every way that can be tested to Bohr's version of quantum physics, the Copenhagen Interpretation.

Revised slightly in the light of Wheeler's comments, the 137-page dissertation typed up by Nancy was circulated to various experts, including Niels Bohr, for further comments in January 1956. Everett left Princeton in the spring of 1956 to take up a career with the Pentagon, working on highly classified material for the Weapons Systems Evaluation Group, in which he soon became head of the mathematics division. Much of his work there is still classified, but it is understood to have involved, among other things, determining the best methods for selecting targets for nuclear attack, and the development of the concept of Mutually Assured Destruction (MAD). Everett returned to Princeton in September for his final examinations, and submitted a much shorter version of his thesis, revised in response to the comments he had received and with considerable advice on presentation from Wheeler, in March 1957. The 'splitting' did not appear in the final version, Wheeler having convinced Everett that as far as getting his PhD was concerned, discretion was the better part of valour.

Everett formally completed the requirements for his PhD in April 1957, and a paper which is essentially the same as the final version of his PhD thesis was published in the journal *Reviews of Modern Physics*, under the title '"Relative State" Formulation of Quantum Mechanics', in July that year. Hardly anyone took any notice. One of the few people who did express interest in the work was the physicist Bryce DeWitt, but even he was initially opposed to the idea that the physical world could divide repeatedly each time it was faced with a quantum choice. Persuaded by Everett that there was something more to the idea than abstract philosophizing, DeWitt was eventually instrumental in drawing the many worlds idea to the attention of a wider audience – but that wouldn't happen for more than a decade.

Everett chose the term 'relative state' to emphasize the relationship between his ideas and those of Einstein's general theory of relativity. In Einstein's theory, there is no special place in the Universe – all observers are equally entitled to their point of view. In Everett's theory, although he did not express it in quite this way, there is no special universe in the Multiverse – all quantum states are equally real. Combining this with Einstein's insight, *all observers in the Multiverse are equally entitled to their point of view*. In a paper that appeared alongside Everett's paper in *Reviews of Modern Physics*, Wheeler drew attention to this. 'Nothing quite comparable can be cited from the rest of physics,' he wrote, 'except the principle in general relativity that all regular coordinate systems are equally justified.' All observers are equally real. Although the Many World's Interpretation is not the only version of the Multiverse, there is nothing in any of the variations on the theme to refute this insight.

It's worth emphasizing this, because people still argue about what the 'relative state' formalism actually means physically, as if Everett had left it ambiguous in some way. Far from it. Quite apart from the references to splitting and intelligent amoebas that Wheeler persuaded him to leave out of his thesis, in a footnote to the *Reviews of Modern Physics* paper Everett wrote, 'From the viewpoint of the theory, *all** elements of a superposition (all "branches") are "actual", none any more "real" than the rest. It is unnecessary to suppose that all but one are somehow destroyed.' And in the long draft version† he wrote:

> At this point we encounter a language difficulty. Whereas before the observation we had a single observer state afterwards there were a number of different states for the observer, all occurring in a superposition. Each of these separate states is a state for an observer, so that we can speak of the different observers described by the different states . . . In this situation we shall use the singular when we wish to emphasize that a single physical system is involved, and the plural when we wish to emphasize the different experiences for the different elements of the superposition. (e.g., 'The observer performs an observation of the quantity A, after which each of the observers of the resulting superposition has perceived an eigenvalue.')

He also had a ready response for people who asked why we don't feel any of this splitting. The *Reviews of Modern Physics* paper again:

> [The] total lack of effect of one branch on another also implies that no observer will ever be aware of any 'splitting' process.
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> Arguments that the world picture presented by this theory is contradicted by experience, because we are unaware of any branching process, are like the criticism of the Copernican theory that the mobility of the earth as a real physical fact is incompatible with the common sense interpretation of nature because we feel no such motion. In both cases the argument falls when it is shown that the theory itself predicts that our experience will be what in fact it is. (In the Copernican case the addition of Newtonian physics was required

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* His emphasis.

† Published in the collection of papers edited by DeWitt and Graham.

to be able to show that the earth's inhabitants would be unaware of any motion of the earth.)

But the universes would be completely cut off from one another after the split: 'There is no possible communication between the observers described by these separate states,' Everett wrote in the draft thesis.

THE BRANCHING TREE OF HISTORY

Communication between the different branches of Everett's Multiverse, sometimes known as 'parallel worlds', would be impossible, according to the same equations that describe the existence of such multiple realities. Except for one intriguing possibility, which is strictly outside the scope of this book, but too enticing to resist mentioning briefly.

That possibility is time travel. The idea of parallel worlds is one of many which appeared in science fiction long before it became respectable science; another is the idea of time travel. In many parallel-universe stories, either the protagonists are somehow shifted 'sideways in time' into another universe, or the entire story is set in a parallel reality, an alternative history that has branched off from our own timeline at some critical point in the past – for example, where the Axis powers won the Second World War.

The resulting image we have is of history as a tree with many branches, representing different universes that exist because they branch off at different times according to different such outcomes; the analogy is actually far from perfect, since if Everett is right there is no 'main trunk' for the tree, and the branching is more complex, but it will do. Many time-travel stories involve travellers who go back in time and, either deliberately or accidentally, change history so that they return to a 'present' very different from the one they set out from.

Combining these two ideas, a traveller might go back in time down one branch of history (in one universe), then forward in time up another branch (another universe). It isn't that he or she has changed history; both versions always existed. In the classic 'granny paradox', for example, a traveller goes back in time and accidentally causes the death of her own grandmother, before the traveller's mother has been born. In that case, if there is only one timeline, the traveller is never born, so she never goes back in time, so granny survives – and so on. In the many worlds version of the story, the traveller goes back and granny is killed, but this is the branching point for another universe. The traveller might go forward in time up the alternative branch to find a present where she had never existed, or she might go back up her original branch to find, to her surprise, that granny wasn't dead after all. Either way, there is no paradox.

It all makes for entertaining fiction. The surprise for us is that there is nothing in the known laws of physics to prevent time travel, although it would be extremely difficult to build a time machine.* The equations of the general theory of relativity (the best theory of space and time we have, which has passed every test yet devised) allow for the possibility of time travel; but they don't allow the possibility of travelling back in time before the moment that the time machine is built. This is why we are not overrun with visitors from the future. The time machine hasn't been built – yet.

But getting back to the Multiverse, the granny paradox reminds us of the parable of Schrödinger's cat. This is just the kind of puzzle that Everett's Many Worlds Interpretation resolves.

Because of the way the original cat puzzle is set up, there are only two possible outcomes – two 'eigenvalues' in the language of quantum physics. The cat is either dead or alive. According to Everett's interpretation, this means that there are two equally real worlds, superimposed on one another, but never able to influence each other – a universe with a dead cat and a universe with a live cat. It is easy to imagine a more complicated scenario, with the outcome determined by the equivalent of rolling dice, in which there might be many more possible results. Extending Schrödinger's own idea, there might be a couple of dozen cats housed in their own compartments, and which one gets killed would depend on the outcome of the roll of the dice. There would be a corresponding number of parallel universes after the experiment was carried out, with a whole variety of quantum cats to consider. But not, as is often assumed, an infinite number of parallel

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* See Kip Thorne's book. Thorne, incidentally, was another of Wheeler's students.

universes. Although the 'many' in the Many Worlds Interpretation would be an incomprehensibly large number, there is no reason to think that it would actually be infinity. In this vast stack of parallel universes, the universe next door would be almost indistinguishable from our own, universes slightly farther away would be more different, having branched off from ours at earlier times, and universes far away across the Multiverse would be utterly different from our own.

The best reason for taking the Many Worlds Interpretation seriously is that nobody has ever found any other way to describe the entire Universe in quantum terms. Wheeler realized this from the very beginning; in his 1957 *Reviews of Modern Physics* paper, his final sentence read:

> Apart from Everett's concept of relative states, no self-consistent system of ideas is at hand to explain what one shall mean by quantizing a closed system like the universe of general relativity.

In 1957, such a statement made less impact than it does today. Fifty years ago, our understanding of the Universe was much more limited than it is now – so much so that there was still a lively debate between those cosmologists who argued that the Universe as we know it had begun in a Big Bang at a definite moment in time, and those who argued that it had existed forever in a Steady State. One of the great scientific achievements of the late twentieth and early twenty-first centuries has been to establish that the Universe did begin in a Big Bang, almost exactly 13.7 billion years ago, and has been expanding ever since in line with the description of space and time provided by the general theory of relativity. The more sure cosmologists are that they understand the Universe we see around us, the more obvious it is that the only way to reconcile this view with quantum physics is to take on board the Many Worlds Interpretation – which is why Everett's ideas are now regarded as more respectable than ever.

EVERETT COMES IN FROM THE COLD

It was Bryce DeWitt who first made the specialists, and then, indirectly, the general public, aware of Everett's work. DeWitt had known about it from the start, and corresponded with Everett in 1957; indeed, the note in the *Reviews of Modern Physics* paper comparing the lack of any sense of splitting with the lack of any feeling of the earth's motion stemmed from that correspondence. DeWitt was nearly eight years older than Everett (he had been born on 8 January 1923), and had graduated from Harvard in 1943. Because of war work, he only completed his PhD (also at Harvard) in 1949, and after short spells in India and Europe (he married a French physicist, Cecile Morette) he settled down at the University of North Carolina in Chapel Hill, where he worked on the quantum theory of gravity.

In 1968, by which time he was a senior figure in the field, DeWitt received a visit from the physicist and philosopher of science Max Jammer, who was planning to write a book about the history of quantum physics and its various interpretations. To DeWitt's surprise, it turned out that Jammer had never heard of Everett, and he realized that the 1957 paper had been almost entirely forgotten (as it happens, there was a reference to the 1957 paper in a list in a footnote in an earlier book by Jammer, but he wasn't the first person to include in such a list references to papers he hadn't actually read). DeWitt decided that, since Everett was no longer working in physics, he would try to rectify the situation himself, and wrote an article on the Many Worlds Interpretation which appeared in the magazine *Physics Today* in September 1970. It was this article that made many physicists (including myself) aware of Everett's work. It refers to 'the universe as continually splitting into a multiplicity of mutually unobservable but equally real worlds', discusses Schrödinger's cat, and spells out that 'every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself.'

DeWitt describes 'the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense. Here is schizophrenia with a vengeance.' He uses the analogy that '[the] state vector is like a tree with an enormous number of branches,' but makes the point that 'the wave function of a finite universe must itself contain only a finite number of branches.' Everett is on record (see the article by Shikhovtsev) as saying that he 'certainly approves of the way DeWitt presented his [Everett's] theory'.

Many of these ideas were further elaborated by DeWitt's student Neill Graham in his PhD thesis, and together DeWitt and Graham edited a book, *The Many-Worlds Interpretation of Quantum Mechanics*, which appeared in 1973 and included Everett's longer version of his thesis, his and Wheeler's *Reviews of Modern Physics* papers, and the article from *Physics Today*. It was this book that popularized the term 'Many Worlds Interpretation', and in the opening paragraph of their Preface the editors refer to 'a reality composed of many worlds . . . reflecting a continual splitting of the universe'. In 1974, Jammer's book* appeared, with a substantial section on the Many World's Interpretation. 'The multiuniverse theory,' he wrote, 'is undoubtedly one of the most daring and most ambitious theories ever constructed in the history of science.'

DeWitt and Graham spread the word about Everett and the Many Worlds Interpretation to physicists; it was spread farther in December 1976, when an article appeared in the 'Science Fact' column of the SF magazine *Analog* under the title 'Quantum Physics and Reality'. The subheading read 'Alternate universes are not merely gimmicks for SF writers – they're necessary for the salvation of quantum physicists!' and authors Michael Talbot and Lloyd Biggle Jr gave a clear account of the idea.

Since more people (especially students) read *Analog* than bought *The Many-Worlds Interpretation of Quantum Mechanics*, this raised Everett's profile to its highest level. By this time, both DeWitt and Wheeler were working at the University of Texas at Austin, where in 1977 they organized a meeting to discuss the problem of consciousness and whether a computer could ever be conscious. Everett was invited to attend and was the star of the show, speaking to a packed audience;

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* *The Philosophy of Quantum Mechanics*, Wiley, New York.

the ‘no smoking’ rule in the auditorium was suspended during his four-hour talk for his personal benefit – Everett was a chainsmoker who couldn’t work without a cigarette.

This would be Everett’s last ‘public appearance’, and the only one he made as a famous scientist; but perhaps the most significant event that occurred on that trip to Austin was his meeting with one of Wheeler’s students, David Deutsch, from England. Deutsch was in effect DeWitt’s student as well, and was deeply interested in the nature of the ‘universes’ which are described by the equations of quantum physics. The two of them discussed the issue intently over lunch one day, and Deutsch recalls that Everett was extremely enthusiastic about the term ‘many universes’, and not wedded to the more abstract technical term ‘state vector’.

Deutsch went on to become the leading proponent of the many worlds idea. He is now at the University of Oxford, and has recently made a significant breakthrough by showing how the probabilistic rules of the quantum world arise naturally in the Many Worlds Interpretation – the way the branching gives us the illusion of probabilistic outcomes of measurements.

But if the story of Everett’s version of quantum physics has a happy ending, the same cannot be said of the man himself. A former colleague, John Barry, has described him as ‘brilliant, slippery, [and] untrustworthy’.* He was a cold individual who loved computers but was almost a stranger to his own family, smoked and drank to excess (he was probably an alcoholic) and had an unhealthy diet – he would argue vociferously with anyone who would listen that medical science was mistaken about cholesterol being dangerous. On 19 July 1982, medical science had the last word, when Everett was found dead in bed of a heart attack, at the age of 51. It was twenty-five years, almost to the day, since the publication of the *Reviews of Modern Physics* article. In 1996, Everett’s daughter, Liz, committed suicide, and in 1998 his wife, Nancy, died of lung cancer – possibly a passive victim of Everett’s smoking habit. The surviving member of the family, Hugh Everett’s son Mark, found fame as a song writer and leader of the band Eels; his gloomy music provides a graphic insight into what life

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* *Scientific American*, December 2007, p. 78.

was like growing up with such a dysfunctional father. We can only hope that things turned out better for all of them in some of the other universes.

Which brings me back to the one thing that makes the whole Many Worlds Interpretation stick in people's throats. It seems so extravagant in terms of universes! It makes complete sense in terms of the physics and mathematics, and it is particularly sparing in terms of assumptions – the only assumption Everett made was that the equations are telling the truth. But, as DeWitt said, 'the idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense.'

Let's face it – what we human beings are really interested in is how *we* got to be here, and where our own world is going; surely you only need one physical world to account for the fact that we are here? That's what people used to think. But over the past two decades it has become increasingly clear that there is something odd about our Universe – something odd which allows us to be here to ask such questions. This provides a powerful incentive to take the Multiverse seriously, irrespective of the specific merits of Everett's archetypal variation on the theme. It is quantum physics that gives a solid scientific basis to the Multiverse idea; but it is the existence of an array of cosmic coincidences that points up the need for such an idea in the first place.