Philip Ball – Beyond Weird

Philip Ball's book 'Beyond Weird' (Bodley Head 2018) is by far and away the best book I have read on Quantum Theory (and I have read quite a few). While it is accessible to the layman, one gets the impression that Ball really knows what he is talking about and his analysis of the current state of play in the field is exemplary.

However, it is hardly possible to write a single sentence about quantum theory without disagreeing with someone and, naturally enough, I found plenty to disagree with. The comments that follow are certainly not criticisms; they are simply my attempt to help us get 'beyond weird'.

Page 11

Ball lists 6 quantum phenomena which are generally regarded as 'weird'. They are:

1. Wave-particle duality – the fact that objects can apparently exhibit both particle-like and wave-like behaviour simultaneously
2. Superposition – the fact that objects can appear to be in two different states at the same time
3. The uncertainty principle – the fact that measuring one property restricts the accuracy with which you can measure its conjugate property
4. Entanglement – the fact that two widely separated objects can appear to behave like one system with a set of shared properties.
5. The apparent impossibility of measuring a property of a system without disturbing the property you are trying to measure
6. The idea that in a quantum system everything that can happen really does happen

My list would be slightly different. No. 5 – the impossibility of measuring something without disturbing it – is not unique to quantum systems. Moreover it is perfectly possible to make a measurement on a quantum system (e.g. the polarisation of a photon) without disturbing it (in the sense that repeated measurements of the same quantity will always give the same results). When measurement does appear to disturb the thing being measured (for example when an attempt is made to discover which way an electron went in an interferometer) it is always because the object under scrutiny is in a superposition of states. No. 5 is therefore subsumed by No. 2.

No. 6 – the claim that everything that can happen does happen – is properly confined the certain *interpretations* of QM; it is not a general feature of all quantum systems.

My list would contain the following items.

1. Wave-particle duality
2. Superposition
3. The uncertainty principle
4. Entanglement
5. The measurement problem and/or the collapse of the wave function
6. The breakdown of causality – the fact that quantum systems can apparently behave randomly

Ball goes on to say that Quantum Theory '*says none of these things*', they are all '*interpretations laid on top of the theory*'. I think this is unfair. It is demonstrably true that electrons and photons have both particle-like and wave-like properties and it is perfectly reasonable to say that Quantum

Theory[1] forces us to accept the existence of a phenomenon which we call the 'wave/particle duality'. To take an analogous example, Newton's laws of motion and gravity provide a superb example of a set of equations which allow us to make astoundingly good predictions about the behaviour of the solar and other systems. It is perfectly possible to write these equations down without anywhere using the idea of a force as follows:

$$\ddot{r} = \frac{GM}{r^2} \tag{1}$$

Newton's law could be stated in the following way: Every body in the universe accelerates towards every other body in the universe with an acceleration which is proportional to the mass of the other body and inversely proportional to the square of the distance from that body. We do not have to mention the word force (nor, indeed, do we need to bring in the mass of the target object – an omission which is certainly an improvement). So, it can be argued, the idea of 'force' is an unnecessary *interpretation* of the equations and is not, strictly part of the theory.

But in spite of this, Newton was quite right to call the gravitational effect of one body on another a 'force' because of the way we use the word to describe other, more familiar situations such as a horse pulling a cart or knife cutting cheese. Likewise the words superposition and entanglement have been chosen to describe certain quantum phenomena precisely because they have other more familiar meanings which mirror some aspects of the behaviour we are trying to describe. These words are therefore not mere *interpretations* of QT, they are the names we assign to phenomena which we wish to interpret.

Pages 12-21

Ball argues that recent experimental results and a consequent deeper understanding of QT mean that the time is right for a renewed effort to find a '*set of simple and physically intuitive principles, and a convincing story to go with them*.' He warns us that '*it is possible that we might never be able to say what quantum theory means*' but he urges us abandon the habit of just labelling quantum phenomena as 'weird'. I entirely agree. I believe that it may indeed be possible to find such a set of principles and a convincing story to go with them. Indeed, I may as well admit at the outset that I have such a story in mind but before revealing my hand too soon, I wish to see how my ideas fare in comparison with the more conventional interpretations which Ball goes on to describe.

Pages 32-4 – the reality or otherwise of 'states'

Ball agrees with Susskind that '*the key distinction between classical and quantum mechanics is that ... quantum physics has a different relationship between the state of a system and the results of a measurement on that system*.'

While this is, in a sense, true I think that the words Susskind uses force us to make unwarranted assumptions. In particular I am unhappy about the phrase '*the state of the system'.* It may seem self evident that if you have a *system* (eg a radioactive atom) it must be in a *state* (decayed or undecayed) – but we (and Susskind) know this to be false because a quantum system can be in a superposition of states. Let us therefore be generous and assume that Susskind actually meant to say '*state (or states) of a system*'. But even this formulation makes unwarranted assumptions. It is perfectly possible to maintain, for example, that the radioactive atom does not even exist before it is detected and measured. I do not subscribe to this view because it effectively negates any attempt at doing science; but I believe there are other alternatives which need to be taken seriously. What if the state of the atom is *undecided*? That is to say, there are two possible states for the atom (decayed

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[1] Ball actually uses the phrase 'quantum mechanics' not 'Quantum Theory' and since the former is a mathematical method for getting results, Ball is technically correct when he claims that quantum mechanics says nothing about '*how things are*'. The book, however, is not about quantum *mechanics* it is about Quantum *Theory* so I will not allow him to hide behind this particular arras.

and undecayed) but which state the atom is in has not yet been determined. (I am effectively suggesting something very like the game of 20 questions in which the 'answer' is not decided until the questions are asked – see page 350.)

To put my objection another way, I am saying that Susskinds use of the phrase '*state of the system*' assumes a kind of reality which may not in fact exist.

Pages 38-57 – the wave/particle duality

In the next chapter Ball discusses the wave/particle duality. Here again we are faced with the fundamental question of what counts as *real*. Is the electron the real object whose behaviour is described by a wave equation; or it the wave the actual reality out of which the electron emerges?

I like to think of these two alternative views through two analogies.

Imagine a Martian viewing Earth through a telescope. He sees lots of snake-like entities moving about on the surface of the Earth which appear to follow definite wiggly lines. Close observation reveals that the snakes leave a point known as point L at regular intervals and travel at an approximately constant speed towards a point E. Likewise other snakes leave E and travel towards L at about the same intervals. Eventually our Martian friend constructs a snake timetable which completely describes the movements of all the snakes between L and E. Being an astronomer, our Martian friend is convinced that the snakes are real and that they are obeying some kind of rule but his mathematical friend maintains that what he is looking at are just emergent phenomenon and the only reality out there is the rule.

Super Mario is a classic role playing game dating from the 1990's. In it, the gamer, in the character of Mario, has to rescue Princess Peach from various evils by running and jumping, throwing fireballs etc. etc. The game could not be played if the characters involved did not obey certain rules which gives the situation a sense of reality. For example, if the Princess is seen in one room, she will still be there if you go back at a later time. Modern video games can be so real that gamers can literally lose themselves in a virtual reality while playing the game. Indeed, there is a perfectly valid context in which you can assert the reality of Mario and his friends without contradiction. But of course, we know that Mario is not real. He is an 'instance' of a 'class' in an 'object-oriented program' which is running under an 'operating system' in an electronic machine.

Is an electron like a 'snake' operating to a timetable, or is it more like Mario, an emergent property of an underlying mathematical structure? I believe that this is one of the most important issues which we must resolve in Quantum Theory.

The issue is brought into sharper focus when Ball discusses systems which are in a superposition of states

Pages 60-73 - superposition

On page 63 Ball explains how, given a certain system such as a single electron in a potential well, we can write down an equation (the Schrödinger equation) to describe it. But this equation does not, in general have a unique solution, it has many different solutions all of which describe possible states which the system might be in. What is more, since the Schrödinger equation is linear, any linear combination of these states is also a possible solution.

The situation is, in fact, exactly analogous to the plucking of a violin string. The equation which describes this situation looks like this:

$$\frac{\partial^2 y}{\partial t^2} = c^2 \frac{\partial^2 y}{\partial x^2} \qquad (2)$$

Given the boundary condition that y must be zero at $x = 0$ and at $x = l$ this equation has many 'solutions. The simplest solution is

$$y = A\sin\left(\frac{\pi}{l}x\right)\sin\left(\frac{\pi c}{l}t\right) \tag{3}$$

which describes a string vibrating in its fundamental mode. But this is also a solution:

$$y = A\sin\left(\frac{2\pi}{l}x\right)\sin\left(\frac{2\pi c}{l}t\right) \tag{4}$$

which describes a string vibrating in its first overtone mode. In fact there are an infinite number of solutions, each describing another possible mode of vibration. Note that none of these solutions tell us *how* the string is actually vibrating, they only tell us what is possible.

That is not all. Since the wave equation is linear, this is also a solution

$$y = A\sin\left(\frac{\pi}{l}x\right)\sin\left(\frac{\pi c}{l}t\right) + B\sin\left(\frac{2\pi}{l}x\right)\sin\left(\frac{2\pi c}{l}t\right) \tag{5}$$

which describes a string vibrating in two different modes simultaneously.

When we apply similar reasoning to an electron in a potential well we have to conclude that an electron can exist not only in one of its singular energy states – it can also exists in a superposition of several states at once.

The central question, therefore, is how do we *interpret* these multiple states. Do we follow de Broglie and say that the electron really does exist but its behaviour is somehow 'guided' by the wave function in much the same way as trains are guided by the railway timetable. Or do we follow Tegmark and deny the existence of electrons and admit only the mathematical substructure in the same way that we would normally deny Mario's existence except as an instance of a class. Or do we take Bohr's advice and just not ask the question?

Ball is convinced that we should ask the question and I entirely agree with him. The trouble is that the best brains in the world have been grappling with it for the best part of a century so what chance is there that a humble physics teacher (retired) like myself can make a sensible contribution to the debate? Is it conceivable that the reason why the best brains in the world have not come up with an answer is that the language we have been accustomed to use to describe quantum phenomena forces us to make assumptions about the nature of reality which are, in fact, not justified?

When we use the word 'reality' we tend to think of 'what exists' or 'what happens'. More specifically 'what exists or happens *now*'. But there is more to reality than this. In the first place, Special Relativity tells us that different observers have different 'nows' so either reality includes more than 'what exists now' or alternatively, every observer has a different reality. If I were to ask 100 physicists which of these options they would subscribe to, my guess is that the vast majority would be happy with the second, relativistic alternative. But if every observer has a different reality, how do we make sense of our individual experiences? Surely an objective, observer independent view of the world must accept that reality is not a binary property. Objects can do more than just 'exist' or 'not exist'. Different events can have different 'reality status' – not just either 'happened' or 'not happened'. Even in a classical world the reality status of a past event is different from the reality status of a present event. In a relativistic world the reality status of a supernova explosion whose light has not yet reached us is different from the reality status of the supernova of 1054 (now visible to us an known as the Crab Nebula).

My position is that quantum phenomena force us expand the meaning of the word 'reality' yet further to include objects which *may* be in a certain state and events which *may* have happened. The status of these objects and events is *undecided*. Examples include the exact position of an electron in a box before it is measured or the decay of a radioactive atom before its product has been detected. Eventually (I believe) all such events will acquire the universal status of either 'happened' or 'not happened' but this period of uncertainty can last for a significant period of time. During this time I like to speak of reality being 'suspended' for a while. (An alternative form of words is to say that, following Everett, the world has split into multiple different copies but personally I do not find this image at all appealing.)

Ball then goes on to discuss the famous double slit experiment using individual photons or electrons about which Feynman famously said "[It] is absolutely impossible to explain in any classical way and has in it the heart of quantum mechanics. In reality, it contains the only mystery." I do not believe that it is the only mystery but if anyone can explain it using simple physical principles and a convincing story to go with it, we are well on the way towards a true understanding of quantum phenomena.

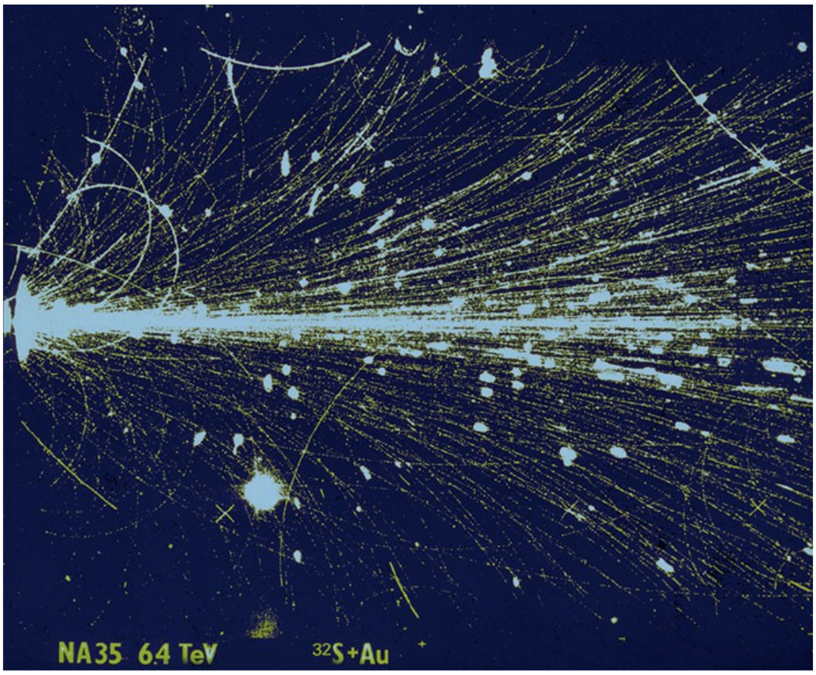
Well, there is really no difficulty about the simple physical principles involved. The interference pattern clearly indicates the wave nature of the phenomenon. What we have to do is provide a convincing story to go with it which explains how a single particle can follow a particle-like trajectory and yet interfere with itself without resorting to nonsensical phrases like 'the particle passes through both slits at once'. Here is my attempt.

When the electron leaves the gun reality is suspended for a while. All sorts of possibilities emerge, one of which is the possibility that the electron passes through slit A; another is that it passes though slit B. (It is also possible that the electron veers of sideways and goes through neither of the slits but we usually ignore these.) Further possibilities arise after the electron has passed through the slit because its trajectory will bend due to diffraction. Immediately before the electron hits the detector these possibilities have the reality status of being *undecided* but the *probability* of each possible trajectory is determined by physical law (namely the Schrödinger equation). When the electron is finally detected on the screen, *one and only one* of these possibilities is elevated from the status undecided to the status of having actually happened.

Two things should be said straight away about this story. Nowhere have I said that the world splits into multiple copies of itself; nor is there any need for 'backward causation' as is required by some other interpretations of QT. On the other hand, it will readily be seen that my story contains some elements of both these ideas. It also contains an element of Bohr's philosophy because while the trajectory remains undecided, it does not make sense to ask 'which way is the electron going?'. But unlike the Copenhagen approach, is is (I believe) sensible to ask the question 'which way did the electron go?' *after* it has been detected on the screen. Indeed, the The Elitzur–Vaidman bomb-testing experiment does exactly that.

Whatever you may think of this story, it is immediately obvious that we run into big trouble when the electron finally hits the screen. What causes just one of the potential realities to become the real reality. In short – what happens when we make a *measurement*?

But before we explore this problem I should like to return for a minute to the question of whether objects like electrons and photons are real objects (like trains) or just emergent phenomena (like the characters in a computer game). I have to admit that, like William Bragg, I have sometimes been guilty of believing that electrons are waves on Mondays, Wednesdays and Fridays, and believing that they are particles on Tuesdays, Thursdays and Saturdays. On Sundays I don't know what to think. But at the end of the day, the concept that electrons and photon are real particles is too useful to be discarded. Take the image (on the following page) of a particle collision in a bubble chamber. To maintain that all those tracks are just disturbances in some underlying mathematical field is just not helpful (even though it might possibly be true.) The situation is much the same as regards our present understanding of gravity (as being the result of a warping of space-time). While everyone knows this to be the real truth, the rocket engineer who is calculating the required trajectory of a mission to Mars is content to assume that Mars exerts a thing called a 'force' on the probe whose strength is determined by Newton's law. For him, 'forces' are as real as Mars itself. The word 'force' is just the name we give to the phenomenon of mutual attraction which acts as a result of Einstein's theory. And if you are faced with a pedant who insists that forces do not exist, try dropping a heavy weight on his toe!



In my view, therefore, electrons and photons are as real as tennis balls and planets, but when such a particle is in a state of 'suspended reality' its status is 'undecided' and while in this condition, all we can do it track its possible progress using the wave equation. Eventually, however, when the particle interacts with the environment, its status and history is determined retrospectively. The wave equation is seen to be just a mathematical tool for making predictions; it has no reality independent of the object whose probability it describes. If you ask me 'yes, but what guides the particle into one path and not another?' I answer that nothing guides it. It just does what particles do, in the same way that nothing 'guides' the path of a tennis ball, it just does what tennis balls do namely – continues in a straight line unless acted on by an external force.

Now we must face the difficult question of what causes the state of 'suspended reality' to come to an end; or, in more conventional language, what causes a quantum state to revert to being a classical one.

Pages 78-101 – the measurement problem

Regrettably, Ball confuses this problem by talking about two completely different issues in the same chapter. The first issue is the question of whether the act of making a measurement on a system changes the system we are trying to measure; while the second concerns the so-called 'collapse of the wavefunction'.

We can dispense with the first problem easily. Yes it is true that making a measurement on a system we can apparently change its properties. If we measure the orientation of the spin of an electron in the vertical plane we will find that it is either up or down. If we measure its orientation using a horizontal detector we will find that it is either left or right. These results are mutually contradictory because it doesn't make sense to say that its orientation is both horizontal and vertical at the same time. (You can't claim that its original orientation was at 45° either because a measurement made at 135° will also yield a positive result.) But as I have indicated earlier, this is the same problem as the problem of superposition. The wavefunction which describes the state of the electron allows of multiple possibilities. In my terminology, the state of the electron is *undecided* until the moment of measurement. It is as if you have a box containing a magic tie. If you open the box at one end, the tie will be found to be either red or blue; but if you open the box at the other end, it will be found to be either green or yellow. Does opening the box change the colour of the tie in the box? Emphatically no. The truth is that before you open the box the colour of the tie is *undecided*. When you open the box at the red/blue end and pull out a red tie, you haven't changed the colour of the tie. It always was red. All that changes is that the probability that the tie was green collapses to zero.

In the delayed choice experiment an attempt is made to force nature to reveal her hand by setting up the crucial part of the experiment *after* the electron has supposedly gone through one slit or the other. This is rather like telling your wife that you would much prefer a red tie to a green one for Christmas *after* the shops have closed. But what if your wife buys ties of *both* colours on credit and discards the unwanted one afterwards? Would you ever want to claim that the tie she gave you had changed colour?

The real problem, however, comes with the moment of measurement. Any interpretation (apart from Everett's Many Worlds interpretation) must come to grips with the problem of defining precisely what constitutes a *measurement*. Ball says (page 96) '*Before measurement the system is fully described by a wavefunction from which one can calculate the various probabilities of the different possible measurement outcomes. But [when a measurement is made] it 'collapses' those possibilities to just one.*' He then goes on to point out that '*The fundamental mathematical machinery of quantum mechanics is unitary*' (i.e. in principle information preserving or reversible) '*Yet every experiment ever performed on a quantum system ... induces what we are forced to call the 'collapse of the wave function' … a necessarily non-unitary* (information destroying or irreversible) *process and therefore inconsistent with what wavefunctions seem able .. to do.*'

Now if we accept that wavefunction collapse is a real physical phenomenon (as indeed pretty well everyone except Everett's followers is obliged to do) then it ought to be amenable to experimental investigation. But as yet, no one has come up with any experiment which allows us to, as it were, observe wavefunction collapse in operation, or to manipulate it for example by delaying it or advancing it. For followers of the Copenhagen interpretation, such experiments are ruled out by virtue of the fact that, since all measurements we can possibly make are macroscopic, wavefunction collapse has always happened before the measurement is made. For others (and this probably includes Ball) wavefunction collapse is the name given to the process by which the information content in a system is reduced e.g. when the experimenter gains some knowledge about the system. He says: '*Wavefunction collapse is a generator of knowledge: it is not so much a process that* gives us the answers*, but is the process by which* the answers are created.'

To a certain extent I agree with this view. When the electron finally reaches a detector, its past history becomes fixed. An answer has been created. But I would still like to know exactly *how* a wavefunction collapses, *what causes* it to collapse and whether we could in principle manipulate the process. And I am not prepared to accept the view that collapse is instigated by 'the act of noticing'. I utterly reject (along with Einstein) the idea that conscious minds have anything at all to do with wavefunction collapse.

There is another issue with wavefunction collapse which Ball barely touches upon. On page 95 he mentions that quantum systems are '*prone to randomness*' Now just because the Schrödinger equation is unitary it does not mean that wavefunction collapse is necessarily a non-unitary process. One possible mechanism which has been proposed is that the (linear) Schrödinger equation which we are all familiar with is only an approximation to a more complex non-linear equation which contains as one of its properties a unitary collapse of the wavefunction when, for example, the function reaches a certain level of complexity. I have in mind the kind of behaviour of the Logistic Equation ($x' = Ax(1 - x)$) when A increases beyond a certain point. In this case the result is chaos but maybe an equation could be devised with collapses to a stable but apparently random outcome.

My gut feeling here is that this search is doomed to failure because I firmly believe that 'God really does play dice'. All the indications are that events like the radioactive decay of an atom or the arrival of an electron at a particular point on a screen are truly random. But this still begs the question what *causes* the collapse into a random outcome and when exactly can we expect collapse to occur. I do not have any answers to these questions but I am convinced that it is something to do with the way all the potential, undecided, realities interact with the environment. When a quantum system is isolated from its environment, reality can remain suspended and the status of the system can remain undecided. As soon as the system comes into (potential) contact with other systems, it becomes more and more difficult to maintain the pretence (in much the same way that the more questions you ask in the 20 questions game, the more difficult it is to think of a consistent set of possible solutions) until eventually, at some point, nature has to give up and say okay, okay this is what really happened. What determines this point is yet to be discovered. There are some who are convinced that gravity has an essential role to play; others put their faith is a concept called decoherence (discussed later). The person who solves this riddle will undoubtedly be hailed as latter-day Newton or an Einstein.

Pages 104-125 – interpretations of QT

Ball describes the major different interpretations of Quantum Theory. I sincerely believe that the alternative interpretation which I have suggested is different from all of them and I would dearly like to know a) if any respected physicist has put forward a similar idea and b) whether the idea can really stand the same sort of scrutiny which the major interpretation have endured.

Cut down to size, you could say that my idea of 'a finite period of suspended reality' is only just Everett's Many Worlds idea plus wavefunction collapse (and many would say that it suffers from the faults of both interpretations!).

Pages 128-143 – quantum spin

Ball illustrates the strange behaviour of quantum logic using the Stern-Gerlach experiment to measure the spin orientation of an electron[2]. He notes two ways in which quantum systems can behave differently from classical ones. Measuring one property (σ_x the spin orientation in the x direction) can affect σ_z and measuring σ_x first and then σ_z gives a different result from measuring σ_z first, then σ_x.

The more I think about this experiment the more troublesome it seems. In fact I find it more troubling than superposition, entanglement or even the measurement problem. The problem is this. First the electron is prepared with spin UP. Repeated measurements of σ_z confirm that it really is in that state and no other. Now we measure σ_x. It is no surprise really when we get the answer LEFT or RIGHT. We can explain this by saying that the original electron was in a superposition of states, those states being UP/LEFT and UP/RIGHT and the act of measurement caused the wavefunction to collapse into one or other of these alternatives. It is in the nature of the experiment that these two states are separated into two different beams. Now comes the crunch. If we attempt to measure σ_z on those electrons which apparently are now in the UP/RIGHT state, we would expect to get the answer UP – but we don't. Sometimes we get UP and sometimes we get DOWN.

It is clear that the two properties UP/DOWN and LEFT/RIGHT spin are not independent of one another and that measuring one genuinely does affect the other.

Now any physical interpretation of QT is going to have difficulty explaining this (with the exception, of course, of the Copenhagen interpretation which simply ignores the problem). My own solution is the recognition that wavefunction collapse is not an all or nothing affair. When the horizontal component of the superposition of states UP/LEFT and UP/DOWN is measured, the wavefunction collapses in such a way as to resolve the horizontal component but randomise the vertical component. The outcome is not either UP/LEFT or UP/RIGHT but it is either a superposition of UP/LEFT and DOWN/LEFT or a superposition of UP/RIGHT and DOWN/RIGHT. This swapping of superpositions can be repeated as many times as you like.

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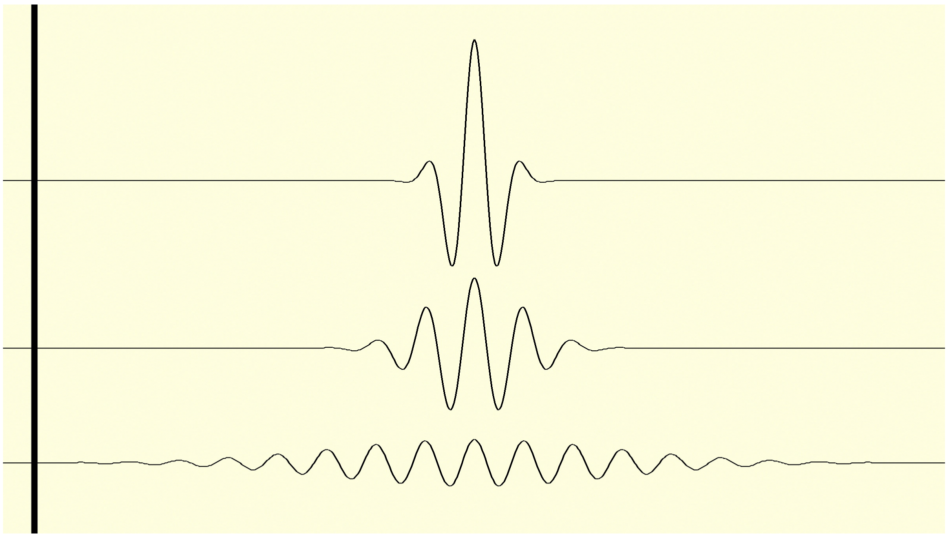
[2] The original experiment involved a beam of silver atoms. If the experiment is done using electrons the effect we are trying to measure will be swamped by the much larger deflection due to the effect of the magnetic field on the electron's electric charge. I am sure Ball is aware of this and only used electrons in his book in order to keep thing as simple as possible. I shall follow his example.

Eventually when the electron is finally absorbed and wavefunction collapse is complete it becomes possible to reconstruct the whole history of the electron and to say with certainty that 'here the electron was spin UP; here it was spin LEFT and here it was spin DOWN' etc.

Pages 146-156 – the Uncertainty Principle

I entirely agree with Ball that nothing in quantum theory is more misunderstood than Heisenberg's Uncertainty Principle. It has nothing to do with the popular idea that, say, if you want to measure the position of a tiny object very precisely, you have to use photons whose wavelength is shorter than the required degree of precision and the energy of these photons will disturb the momentum of the object. Position and momentum are what are called conjugate variables and are entangled together in the same way that the vertical and horizontal components of spin are connected.

Ball tries to explain the principle by appealing to the non-commutative properties of matrices but I cannot say that I understood his argument, nor am I very convinced. If I were to try to explain to someone why it is impossible to measure the position and the momentum of a quantum object simultaneously, I would present them with a diagram of a series of wave packets like this (each or which have the same 'energy') and ask them to measure both the distance of the wave packet from the line on the left and the wavelength of the wave packet as accurately as possible.



These represent three different possible ways of describing a quantum particle of given energy. If you constrain the particle within a small range of possible positions (as in the topmost example) it is difficult to measure the wavelength (and hence the momentum) of the particle precisely. On the other hand, if you choose to allow the particle to spread out, you can measure its wavelength more accurately but not its position. It is not that measuring the position disturbs the wavelength or vice versa; a wave packet doesn't *have* a precisely defined simultaneous wavelength and position. Likewise, a photon travelling through space doesn't actually look like any of these; you can, if you like, think of it being in a superposition of all these possibilities until the photon encounters a specific measuring device. Which state the photon will actually assume will then depend on the nature of the measuring device.

This argument works perfectly in explaining why position and momentum are conjugate variables but I have never seen an equivalent simple argument for explaining why energy and time are conjugate other that that fact that energy × time (like position × momentum) has the dimensions of Planck's constant h. I suspect that the real reason why the Uncertainty Principle holds is due to the underlying symmetries of space-time in much the same way as Noether's theorem relates the conservation laws of energy and momentum to these symmetries. If this is true then I would expect angular momentum and angular position to obey the uncertainty principle as well. In fact I am sure this will be the case but I do not recall having seen this mentioned in any text book I have read.

Pages 160-177 – Hidden variables

It is now well established that no theory involving hidden variables can account for observed quantum behaviour and it is often confidently asserted that the behaviour of entangled particles implies that either we must give up the idea that there exists an objective reality (realism) or that we must accept that some properties of a quantum system are non-local. This issue is discussed in more detail in the next chapter.

Pages 180-195 – spooky action at a distance

Ball's take on this issue is expounded on page 184. He says: '*But this locality is just what quantum entanglement undermines … We can't regard particle A and particle B in the EPR experiment as separate entities, even though they are separated in space.. To put it another way, the spin of particle A is not located solely on A; properties can be* non-local*. Only if we accept Einstein's assumptions of locality do we need to tell the story in terms of a measurement on particle A influencing the spin of particle B. Quantum non-locality is the* alternative *to that view.*'

By rejecting 'spooky action at a distance' Ball appears here to be placing his bets firmly on the non-locality table. His use of the word 'alternative' seems to suggest that if you want to maintain (with Einstein) that objects can only have local properties, then you have to accept instantaneous information transfer. (Einstein's position on this was that since properties can only be local and that instantaneous transfer of information ran counter to the spirit of Relativity, quantum theory must be wrong, or at least incomplete. We now know that he was wrong about this.)

Now it is my belief that there is a way to resolve the apparent paradox and Ball himself gives a hint as to what it might be in the very next paragraph: '*What in fact we are dealing with here is in fact another kind of quantum superposition.*' Exactly! Entanglement is just superposition – nothing more and nothing less. And if you can explain superposition, you should not need to invoke either non-local properties or spooky action at a distance to explain entanglement. Ball goes on to argue that '*although the particles are separated they must be described by a single wavefunction*.' Yes, I agree. But I do not accept that this means that they *share* properties. Or rather, I do not think this is the best way of describing the situation. Let me attempt to explain using a development of the Stern-Gerlach experiment which Ball describes on page 140.

It will be recalled that the spin orientation of an electron[3] can be determined by noting its deflection in a magnetic field. Crucially the measurement always gives a positive (or negative) result; the spin is never zero. Now it is possible to produce electrons in entangled pairs whose spin is always opposite to one another. Alice and Bob agree to make measurements on these entangled electrons and they decide to restrict their measurements to the vertical and horizontal planes only. (That is to say, before each electron is emitted, they set their measuring devices to one or other of these two directions at random.) After they have made hundreds of measurements they compare their results and they find that, in accordance with the predictions of quantum mechanics, every time their measuring devices are in the same orientation, the spins they measure are indeed opposite.

In case all this talk about spins is confusing, let me describe the experiment using the idea of the magic ties which I introduced earlier. You may recall that if you open the left hand end of the box you get either a red or a blue tie, and that if you open the right hand end, you get either a green or a yellow tie. Now Alice and Bob prepare entangled tie boxes which have the additional property that if they both open the same end of their respective boxes they always get ties of different colour. (If they open different ends, the ties can be any colour.)

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[3] See footnote 2

Now suppose that Alice opens the left hand end of her box and the tie in her box 'decides' to be red. How does the tie in Bob's box 'know' that if Bob opens the left hand end too, it must be blue? It looks as if either the red/blueness of the two ties is shared in some way or there is instantaneous communication between the two ties. Any experiment involving 'hidden variables' can be ruled out.[4]

My solution is as follows: when the two boxes (or electrons) are prepared, there are 16 possible combinations of colour (orientations).

	Alice	Bob
1	Red	Red
2	Red	Blue
3	Red	Green
4	Red	Yellow
5	Blue	Red
6	Blue	Blue
7	Blue	Green
8	Blue	Yellow
9	Green	Red
10	Green	Blue
11	Green	Green
12	Green	Yellow
13	Yellow	Red
14	Yellow	Blue
15	Yellow	Green
16	Yellow	Yellow

Four of them are ruled out by the rules of the game (or the laws of physics). Adherents of different interpretations of QT will use different words to describe this situation but we are all describing the same thing. Ball would say that the two boxes are described by a single wavefunction which describes a set of shared properties. He might also add that the two boxes are therefore in a superposition of 12 possible states. Everett would say that the world has split into 12 copies while Bohr was say that, since it is impossible to determine what state the boxes are in, it is pointless even discussing the issue.

I would describe the situation by saying that the system was in a state of 'suspended reality' in which the state of the boxes was undecided but limited to the 12 possibilities listed.

All of us would agree, however, that the rules of quantum mechanics will give the right predictions when the boxes are opened.

Alice now opens the left hand end of her box and pulls out a red tie. I am unsure how Everett and Bohr would describe how the situation changes. Ball, I think, would talk about how the information content of the system has changed by reducing the number of possibilities from 12 to 3 and I largely agree with this. The act of revealing the red tie partially collapses the wavefunction by setting the probabilities of all the options except numbers 2, 3 and 4 to zero. Now when Bob also opens the left hand end of his box, the tie *must* be blue. (If he opens the other end, he will, of course, get either a green or a yellow one.)

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[4] In fact the experiment as described can easily be explained using 'hidden variables' but it turns out that a Stern-Gerlach experiment involving angles other than horizontal and vertical orientation cannot.

Two questions must be addressed. Does this view violate realism or locality or both? Now obviously, my idea that reality can be 'suspended' for a while violates realism – but the important thing about suspended reality is that it is temporary. There is bound to come a time when reality is 'restored'. I believe that this is pretty close to upholding the cause of realism because at the end of the day, when both ties have been revealed, we can confidently say not only what colour they are *now* but what colour they *were all along*. In a sense this could be seen as retrospective or backward causation but it really is no different from the idea that, if the courts decide one day that homosexual relations should be legal, persons previously convicted of the offence should be eligible for compensation.

What about locality? Well, the state of each tie is either red, blue, green, yellow or undecided. It does not 'share' any of these attributes with the other tie, nor does it have to 'communicate' its state to the other tie when its colour is actually decided. There is nothing 'spooky' about the fact that if I find a solitary left-handed glove in one drawer, the solitary glove in the other drawer is right handed. So there is nothing spooky about Bob's tie being blue if Alice's is red. The possibility that both ties were red was ruled out right at the start of the experiment when the boxes (or electrons) were prepared.

Pages 198-216 – decoherence

I find the issue of quantum decoherence difficult to understand – or rather I fail to see how the concept helps to understand how quantum states become classical.

On page 205 Ball states '*if the quantum wavefunctions of two states are not coherent, they cannot interfere, nor can they maintain a superposition. A loss of coherence therefore destroys these fundamentally quantum properties and the states behave more like distinctly classical ones*.'

Now I know that two light beams can exhibit interference only if they are coherent, that is to say, that they maintain the same phase relationship with each other; but in what sense do two quantum states 'remain in step with each other'? When an electron passes through a double slit apparatus and undergoes interference, it is not the case that there is one 'wavefunction' which 'describes and electron passing through slit A' and another which 'describes a different electron passing through slit B'. There is *one* quantum state (a superposition of an electron passing through both slits) and *one* wavefunction which describes the temporal evolution of that state. Perhaps I am just quibbling about words here but I think the analogy (and it is only an analogy) between the Schrödinger 'wave' equation and the behaviour of classical waves can be taken too far. Of course I understand that if you were to mess around with the phase of the particle (as in the experiments by Zeilinger and Arndt described on page 214) you would destroy the interference effect but I fail to see how this furthers out understanding of how quantum states become classical ones.

Take another example. Suppose we have an electron in a potential well in a superposition of two energy states. The wave equation which describes this situation allows both states to exist simultaneously but it does not insist on it. In what sense are these states coherent with each other? And what could we do to disturb the coherence of these states? And if we did disturb the coherence of these states (for example perhaps by vibrating the walls of the box) what would we expect to happen?

Pages 220-236 – pointer states

Part of the answer to the above question is revealed in the next chapter. Apparently not all solutions to the Schrödinger wave equation are equal – some are, in fact, more equal than others. These states (apparently) emerge naturally from the theory of decoherence and are called pointer states. They are characterised by the fact that contact with the environment causes no further 'degradation' of the state. This explains nicely why, since making a measurement always involves contact with the environment, we only ever see pointer states, not superposed ones.

I can think of a useful analogy here. When you pluck a violin string, it vibrates in several different modes at once. In the real (classical) world it is not difficult to design a detector which will measure the amplitude of each of these vibrations individually and produce a frequency histogram. But if the violin string was a quantum object, you would only be able to measure the amplitude of one of the modes and in the process all the other modes would be destroyed. (This is just the same as making a measurement on the vertical polarization of an electron destroys any information you might have had about its horizontal polarization.)

So decoherence seems to supply us with a way of describing how contact with the environment can cause a quantum system to lose its quantum nature and become more like a classical one. I am perfectly happy with this idea as it is perfectly consistent with my own view of what is going on. Lets examine a simple (?) example.

Radon$_{222}$ is an isotope with a half life of about 4 days. What this means is that in any one day there is approximately a 10% chance that it will decay[5]. Suppose we place a single radon atom inside an ionisation chamber containing some molecules of gas. The ionization chamber is sufficiently sensitive that if the alpha particle emitted by the radon atom hits any of the molecules, a chain reaction will occur and the detector will record an event. Let us suppose that it takes a short time T for the emitted alpha particle to reach any of the molecules. Consider the state of the chamber at a certain time t where t is less than T. In my view, the atom is in a state of suspended reality in which the atom is surrounded buy a spherical wavefunction which represents the (tiny) probability that an alpha particle will be found at that point.

Now when t becomes greater than T, the expanding wavefunction will start to encounter the molecules of gas in the chamber each of which will be surrounded by a spherical wavefunction of its own which represents the probability that an electron will be found there created by the collision with the (potential) alpha particle. A short time later, the wavefunction must include the possibility that these (potential) electrons have (potentially) collided with other gas molecules producing (potential) secondary electrons and so on and so on. The number of potential possibilities which the wavefunction must describe quickly becomes mind-bogglingly large as the number of superposed states grows exponentially.

If decoherence theory is correct, many of these potential states will not be coherent with each other and will be disallowed, only those potential pointer states will go ahead to generate further possible states. But even so, the number of possibilities will still go on increasing. Where will it end?

It is clear that decoherence does not actually solve the problem. It is true that when we make a measurement on a quantum system we never see a superposition of states. But what determines *which* of the possible states in superposition do we *actually* see? Ball addresses this important issue in the next chapter.

Pages 240-251 – the problem of Schrödinger's kittens

Ball states (page 245) that most researches believe that '*the sole limits on observing quantum-mechanical behaviour stem from the difficulty of suppressing the environmentally-induced decoherence*.', the implication being that if you could isolate the system sufficiently from the environment, you could, in fact, place a cat in a superposition of live and dead states. I have little time for such speculation. I would much rather believe in the reality of wavefunction collapse and if I was a theoretical physicist at the start of my career would bend my mind towards discovering the mechanism by which this collapse occurs – the when and the why and the how. (The fact that such brilliant minds as Roger Penrose and others have so far not succeeded in doing this would not bode well for my efforts though!)

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[5] The probability is actually log2 / 4 = 0.0753 or 7.5%

Pages 254-285 – quantum technology

My reaction to this is: Maybe – but I am not holding my breath.

Pages 288-305 – many worlds

While I am prepared to accept that the many-worlds interpretation of QT is consistent I reject it for the same reasons that I reject solipsism or creationism. I will have to admit, though, that my own interpretation of QT requires the existence of many (possible) worlds while reality is suspended but I do not ascribe the same level of reality to these worlds as Everett's supporters do as 'I' do not actually have to inhabit any of them.

Pages 308-end – the latest theories

Ball concludes his superb book with a look at the latest ideas and theories. I cannot claim to understand quite where they are all leading but I agree that the search must go on for a new and better way to talk about the mysteries of quantum theory.

An inexplicable omission

Although I am full of praise for the breadth and clarity of Ball's review, I am perplexed by the apparent omission of any proper discussion of what I consider to be the most fundamental question of all. This is the one I listed at the start as number 6. Do quantum systems violate causality? Alternatively Do quantum systems behave randomly?

There are a few scattered references to random behaviour in the book (though the word 'randomness' is not indexed). The longest discussion is on pages 163-165 where Einstein's aversion to 'God playing dice' is referred to but the discussion soon moves on to the question of whether there are 'hidden variables' determining the behaviour of a quantum system. Once we have discovered that there are no 'hidden variables' we are left to assume that Ball is quite happy with the idea that the actual outcome of an experiment is chosen entirely at random – only the probabilities of each possible outcome being determined by the theory.

If this is so, it is the most monumental revolution in the history of physics!

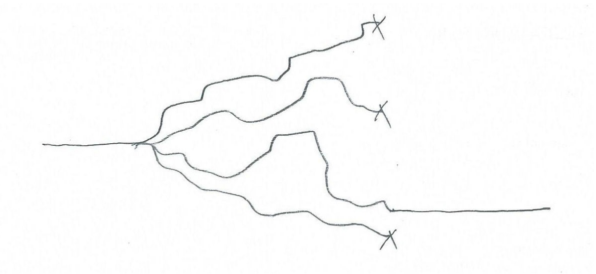
For as long as humans have lived and breathed on this planet it has been an unquestioned assumption that *everything that happens has a cause*. If it wasn't Zeus throwing thunderbolts that caused lightning, it was the build up of electrical charge in the atmosphere; if it wasn't the deluge that created fossils on the tops of mountains then it was the uplifting of the mountains themselves etc. etc.

But with the discovery of radioactivity at the turn of the 20th century, the suspicion arose that some things could, perhaps, happen without a cause. And with the intense discussion concerning the interpretation of QT in the rest of the century, the idea that things could happen at random seems to have been absorbed without serious critical discussion. The reason for this is probably the prevalence of the Copenhagen view which discouraged discussion of anything at all. Then when the idea of hidden variables was thrown out, accepting the existence of random behaviour seemed to be inevitable.

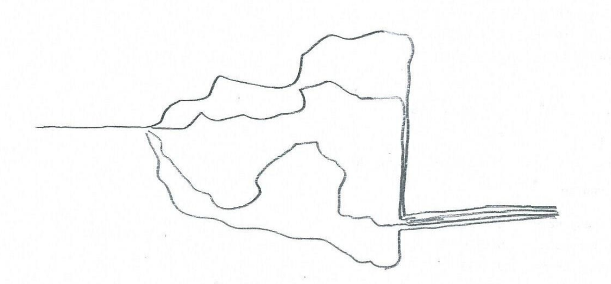
But should we reject thousands of years of reliance on the fundamental principle of causality so easily?

Of course, if you subscribe to the many worlds interpretation you can have your cake and eat it too. Viewed from the perspective of an observer in a single world, the result of the experiment looks random; but if you include the results obtained in all the other possible worlds as well, you can see that they are all, collectively, the result of what went on before.

If, like me, you believe in objective collapse of the wavefunction, you can take either view. If we represent the evolution of a wavefunction as a series of possible diverging world lines, then collapse could come about in one of two ways. Either all but one randomly chosen world line could just stop like this:



or all the world lines could bunch up together so closely that is is impossible to separate them. i.e.



In the former case information is lost but in the latter, causality (and therefore information) would be preserved.

Now as it happens, I am philosophically predisposed to go along the first view but the main thrust of those who wish to explain wavefunction collapse by modifying Schrödinger's equation or introducing gravitational terms would appear to be leading them more towards the second, deterministic interpretation of wave functions collapse. And regardless of your position as regards wavefunction collapse, if you believe that quantum events are essentially random it behoves you to explain exactly how and why the randomness arises.

Again, for what it is worth, I suspect that the answer lies in the structure of space and time at the Planck scale. As far as I am aware, all versions of quantum mechanics – and all interpretations of the theory – tacitly assume that space-time is a continuum. Likewise the wavefunction ψ is assumed to be a continuous, differentiable function of x and t. But what if this is not the case? What if the Schrödinger equation is an *emergent* phenomena like a hurricane. As long as the system is large enough we can ignore the fact that the atmosphere is made of atoms and molecules; but if we study a gas on a microscopic scale we discover new phenomena (like Brownian motion). Similarly, the behaviour of an electron in a hydrogen atom might easily be described by a simple equation – but systems like the decaying radon atom described earlier could be so sensitive to initial conditions that the result might easily be swayed by fluctuations on the Planck scale.

I am astonished that nobody else appears to be troubled by this question. As far as I am concerned, the mysteries of the wave/particle duality, superposition, the uncertainty principle, entanglement and even the measurement problem are largely solved. The existence and origin of randomness, however, is to my mind the biggest mystery of them all.

Carr Bank, 21 May 2018