BEYOND WEIRD

WHY EVERYTHING YOU THOUGHT YOU KNEW ABOUT QUANTUM PHYSICS IS DIFFERENT

PHILIP BALL

Beyond Weird

Why everything you thought you knew about quantum physics is different

PHILIP BALL

THE UNIVERSITY OF CHICAGO PRESS

The University of Chicago Press, Chicago 60637

Published 2018
Printed in the United States of America

27 26 25 24 23 22 21 20 19 18   1 2 3 4 5

ISBN-13: 978-0-226-55838-7 (cloth)
ISBN-13: 978-0-226-59498-9 (e-book)
DOI: https://doi.org/10.7208/chicago/9780226594989.001.0001

Originally published by The Bodley Head, 2018

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA
Names: Ball, Philip, 1962– author.
Title: Beyond weird : why everything you thought you knew about quantum physics is different / Philip Ball.
Description: Chicago : The University of Chicago Press, 2018. | Includes bibliographical references and index.
Identifiers: LCCN 2018008602 | ISBN 9780226558387 (cloth : alk. paper) | ISBN 9780226594989 (e-book)
Subjects: LCSH: Quantum theory—Popular works.
Classification: LCC QC174.123 .B36 2018 | DDC 530.12—dc23
LC record available at https://lccn.loc.gov/2018008602

♾ This paper meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

By way of introduction …

To encounter the quantum is to feel like an explorer from a faraway land who has come for the first time upon an automobile. It is obviously meant for use, and important use, but what use?

John Archibald Wheeler

Somewhere in [quantum theory] the distinction between reality and our knowledge of reality has become lost, and the result has more the character of medieval necromancy than of science.

Edwin Jaynes

We must never forget that 'reality' too is a human word just like 'wave' or 'consciousness'. Our task is to learn to use these words correctly – that is, unambiguously and consistently.

Niels Bohr

[Quantum mechanics] is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature – all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble.

Edwin Jaynes

Arguably the most important lesson of quantum mechanics is that we need to critically revisit our most basic assumptions about nature.

Yakir Aharonov et al.

I hope you can accept Nature as she is – absurd.

Richard Feynman

No one can say what

quantum mechanics means
(and this is a book about it)

Richard Feynman said that in 1965. In the same year he was awarded the Nobel Prize in Physics, for his work on quantum mechanics.

In case we didn't get the point, Feynman drove it home in his artful Everyman style. 'I was born not understanding quantum mechanics,' he exclaimed merrily, '[and] I still don't understand quantum mechanics!' Here was the man who had just been anointed one of the foremost experts on the topic, declaring his ignorance of it.

What hope was there, then, for the rest of us?

Feynman's much-quoted words help to seal the reputation of quantum mechanics as one of the most obscure and difficult subjects in all of science. Quantum mechanics has become symbolic of 'impenetrable science', in the same way that the name of Albert Einstein (who played a key role in its inception) acts as shorthand for scientific genius.

Feynman clearly didn't mean that he couldn't *do* quantum theory. He meant that this was *all* he could do. He could work through the math just fine – he invented some of it, after all. That wasn't the problem. Sure, there's no point in pretending that the math is easy, and if you never got on with numbers then a career in quantum mechanics isn't for you. But neither, in that case, would be a career in fluid mechanics, population dynamics, or economics, which are equally inscrutable to the numerically challenged.

No, the equations aren't why quantum mechanics is perceived to be so hard. It's the ideas. We just can't get our heads around them. Neither could Richard Feynman.

His failure, Feynman admitted, was to understand what the math was saying. It provided numbers: predictions of quantities that could be tested against experiments, and which invariably survived those tests. But Feynman couldn't figure out what these numbers and equations were really about: what they said about the 'real world'.

One view is that they don't say anything about the 'real world'. They're just fantastically useful machinery, a kind of black box that we can use, very reliably, to do science and engineering. Another view is that the notion of a 'real world' beyond the math is meaningless, and we shouldn't waste our time thinking about it. Or perhaps we haven't yet found the right math to answer questions about the world it purports to describe. Or maybe, it's sometimes said, the math tells us that 'everything that can happen does happen' – whatever *that* means.

This is a book about what quantum math really means. Happily, we can explore that question without having to look very deeply into the math itself. Even what little I've included here can, if you prefer, be gingerly set aside.

I am not saying that this book is going to give you the answer. We don't have an answer. (Some people do have an answer, but only in the sense that some people have the Bible: their truth rests on faith, not proof.) We do, however, now have better questions than we did when Feynman admitted his ignorance, and that counts for a lot.

What we *can* say is that the narrative of quantum mechanics – at least among those who think most deeply about its meaning – has changed in remarkable ways since the end of the twentieth century. Quantum theory has revolutionized our concept of atoms, molecules, light and their interactions, but that transformation didn't happen abruptly and in some ways it is still happening now. It began in the early 1900s and it had a workable set of equations and ideas by the late 1920s. Only since the 1960s, however, have we begun to glimpse what is most fundamental and important about the theory, and some of the crucial experiments have been feasible only from the 1980s. Several of them have been performed in the twenty-first century. Even today we are still trying to get to grips with the central ideas, and are still testing their limits. If what we truly want is a theory that is well understood rather than simply one that does a good job at calculating numbers, then we still don't really have a quantum theory.

This book aims to give a sense of the current best guesses about what that *real* quantum theory might look like, if it existed. It rather seems as though such a theory would unsettle most if not all we take for granted about the deep fabric of the world, which appears to be a far stranger and more challenging place than we had previously envisaged. It is not a place where different physical rules apply, so much as a place where we are forced to rethink our ideas about what we mean by a physical world and what we think we are doing when we attempt to find out about it.

In surveying these new perspectives, I want to insist on two things that have emerged from the modern renaissance – the word is fully warranted – in investigations of the foundations of quantum mechanics.

First, what is all too frequently described as the *weirdness* of quantum physics is not a true oddity of the quantum world but comes from our (understandably) contorted attempts to find pictures for visualizing it or stories to tell about it. Quantum physics defies intuition, but we do it an injustice by calling that circumstance 'weird'.

Second – and worse – this 'weirdness' trope, so nonchalantly paraded in popular and even technical accounts of quantum theory, actively obscures rather than expresses what is truly revolutionary about it.

Quantum mechanics is in a certain sense not hard at all. It is baffling and surprising, and right now you could say that it remains cognitively impenetrable. But that doesn't mean it is *hard* in the way that car maintenance or learning Chinese is hard (I speak with bitter experience of both). Plenty of scientists find the theory easy enough to accept and master and use.

Rather than insisting on its difficulty, we might better regard it as a beguiling, maddening, even amusing gauntlet thrown down to challenge the imagination.

For *that* is indeed what is challenged. I suspect we are, in the wider cultural context, finally beginning to appreciate this. Artists, writers, poets and playwrights have started to imbibe and deploy ideas from quantum physics: see, for instance, plays such as Tom Stoppard's *Hapgood* and Michael Frayn's *Copenhagen*, and novels such as Jeanette Winterson's *Gut Symmetries* and Audrey Niffenegger's *The Time Traveler's Wife*. We can argue about how accurately or aptly these writers appropriate the scientific ideas, but it is right that there should be imaginative responses to quantum mechanics, because it is quite possible that only an imagination sufficiently broad and liberated will come close to articulating what it is about.

There's no doubt that the world described by quantum mechanics defies our intuitions. But 'weird' is not a particularly useful way to talk about it, since that world is also our world. We now have a fairly good, albeit still incomplete, account of how the world familiar to us, with objects having well-defined properties and positions that don't depend on how we choose to measure them, emerges from the quantum world. This 'classical' world is, in other words, a special case of quantum theory, not something distinct from it. If anything deserves to be called weird, it is us.

●

Here are the most common reasons for calling quantum mechanics weird. We're told it says that:

- Quantum objects can be both waves and particles. This is *wave-particle duality*.
- Quantum objects can be in more than one state at once: they can be both *here* and *there*, say. This is called *superposition*.
- You can't simultaneously know exactly two properties of a quantum object. This is *Heisenberg's uncertainty principle*.
- Quantum objects can affect one another instantly over huge distances: so-called 'spooky action at a distance'. This arises from the phenomenon called *entanglement*.
- You can't measure anything without disturbing it, so the human observer can't be excluded from the theory: it becomes unavoidably subjective.
- Everything that can possibly happen does happen. There are two separate reasons for this claim. One is rooted in the (uncontroversial) theory called quantum electrodynamics that Feynman and others formulated. The other comes from the (extremely controversial) 'Many Worlds Interpretation' of quantum mechanics.

Yet quantum mechanics says none of these things. In fact, quantum mechanics doesn't say *anything* about 'how things are'. It tells us what to expect when we conduct particular experiments. All of the claims above are nothing but *interpretations* laid on top of the theory. I will ask to what extent they are good interpretations (and try to give at least a flavour of what 'interpretation' might mean) –

but I will say right now that none of them is a very good interpretation and some are highly misleading.

The question is whether we can do any better. Regardless of the answer, we are surely being fed too narrow and too stale a diet. The conventional catalogue of images, metaphors and 'explanations' is not only clichéd but risks masking how profoundly quantum mechanics confounds our expectations.

It's understandable that this is so. We can hardly talk about quantum theory at all unless we find stories to tell about it: metaphors that offer the mind purchase on such slippery ground. But too often these stories and metaphors are then mistaken for the way things are. The reason we can express them at all is that they are couched in terms of the quotidian: the quantum rules are shoehorned into the familiar concepts of our everyday world. But that is precisely where they no longer seem to fit.

•

It's very peculiar that a scientific theory should demand interpretation at all. Usually in science, theory and interpretation go together in a relatively transparent way. Certainly a theory might have *implications* that are not obvious and need spelling out, but the basic *meaning* is apparent at once.

Take Charles Darwin's theory of evolution by natural selection. The objects to which it refers – organisms and species – are relatively unambiguous (if actually a little challenging to make precise), and it's clear what the theory says about how they evolve. This evolution depends on two ingredients: random, inheritable mutations in traits; and competition for limited resources that gives a reproductive advantage to individuals with certain variants of a trait.

How this idea plays out in practice – how it translates to the genetic level, how it is affected by different population sizes or different mutation rates, and so on – is really rather complex, and even now not all of it is fully worked out. But we don't struggle to understand what the theory *means*. We can write down the ingredients and implications of the theory in everyday words, and there is nothing more that needs to be said.

Feynman seemed to feel that it was impossible and even pointless to attempt anything comparable for quantum mechanics:

> We can't pretend to understand it since it affronts all our commonsense notions. The best we can do is to describe what happens in mathematics, in equations, and that's very difficult. What is even harder is trying to decide what the equations mean. That's the hardest thing of all.

Most users don't worry too much about these puzzles. In the words of the physicist David Mermin of Cornell University, they 'shut up and calculate'.* For many decades quantum theory was regarded primarily as a mathematical description of phenomenal accuracy and reliability, capable of explaining the shapes and behaviours of molecules, the workings of electronic transistors, the colours of nature and the laws of optics, and a whole lot else. It would be routinely described as 'the theory of the atomic world':

---

* It's commonly but wrongly believed that Feynman said this. The belief was so widespread that at one point even Mermin began to fear his quip might in fact have been unconsciously echoing Feynman. But Feynman was not the only physicist with a smart line in quantum aphorisms, as we shall see.

an account of what the world is like at the tiniest scales we can access with microscopes.

Talking about the interpretation of quantum mechanics was, on the other hand, a parlour game suitable only for grandees in the twilight of their career, or idle discussion over a beer. Or worse: only a few decades ago, professing a serious interest in the topic could be tantamount to career suicide for a young physicist. Only a handful of scientists and philosophers, idiosyncratically if not plain crankily, insisted on caring about the answer. Many researchers would shrug or roll their eyes when the 'meaning' of quantum mechanics came up; some still do. 'Ah, nobody understands it anyway!'

How different this is from the attitude of Albert Einstein, Niels Bohr and their contemporaries, for whom grappling with the apparent oddness of the theory became almost an obsession. For them, the meaning mattered intensely. In 1998 the American physicist John Wheeler, a pioneer of modern quantum theory, lamented the loss of the '*desperate* puzzlement' that was in the air in the 1930s. 'I want to recapture that feeling for all, even if it is my last act on Earth', Wheeler said.

Wheeler may indeed have had some considerable influence in making this deviant tendency become permissible again, even fashionable. The discussion of options and interpretations and meanings may no longer have to remain a matter of personal preference or abstract philosophizing, and if we can't say what quantum mechanics means, we can now at least say more clearly and precisely what it does *not* mean.

This re-engagement with 'quantum meaning' comes partly because we can now do experiments to probe foundational issues that were previously expressed as mere thought experiments and considered to be on the border of metaphysics: a mode of thinking that, for better or worse, many scientists disdain. We can now put quantum paradoxes and puzzles to the test – including the most famous of them all, Schrödinger's cat.

These experiments are among the most ingenious ever devised. Often they can be done on a benchtop with relatively inexpensive equipment – lasers, lenses, mirrors – yet they are extraordinary feats to equal anything in the realm of Big Science. They involve capturing and manipulating atoms, electrons or packets of light, perhaps one at a time, and subjecting them to the most precise examination. Some experiments are done in outer space to avoid the complications introduced by gravity. Some are done at temperatures colder than the void between the stars. They might create completely new states of matter. They enable a kind of 'teleportation'; they challenge Werner Heisenberg's view of uncertainty; they suggest that causation can flow both forwards and backwards in time or be scrambled entirely. They are beginning to peel back the veil and show us what, if anything, lies beneath the blandly reassuring yet mercurial equations of quantum mechanics.

Such work is already winning Nobel Prizes, and will win more. What it tells us above all else is very clear: the apparent oddness, the paradoxes and puzzles of quantum mechanics, are real. We cannot hope to understand how the world is made up unless we grapple with them.

Perhaps most excitingly of all, because we can now do experiments that exploit quantum effects to make possible what sounds as though it should be impossible, we can put those tricks to work. We are inventing quantum technologies that can manipulate information in unprecedented ways, transmit secure information that cannot be read surreptitiously by eavesdroppers, or perform calculations that are far beyond the reach of ordinary computers. In this way more than any other, we will all soon have to confront the fact that quantum mechanics is not some weirdness buried in remote, invisible aspects of the world, but is our current best shot at uncovering the laws of nature, with consequences that happen right in front of us.

What has emerged most strongly from this work on the fundamental aspects of quantum theory over the past decade or two is that it is not a theory about particles and waves, discreteness or uncertainty or fuzziness. It is a theory about *information*. This new perspective gives the theory a far more profound prospect than do pictures of 'things behaving weirdly'. Quantum mechanics seems to be about what we can reasonably call a view of reality. More even than a question of 'what can and can't be known', it asks what a *theory of knowability* can look like.

I've no intention of hiding it from you that this picture doesn't resolve the ways quantum mechanics challenges our intuition. It seems likely that nothing can do that. And talking about 'quantum information' brings its own problems, because it raises questions about what this information *is* – or what it is about, because information is not a thing that you can point to in the way you can with an apple or even (in some cases) with an atom. When we use the word 'information' in everyday usage it is bound up with considerations of language and meaning, and thus of context. Physicists have a definition of information that doesn't match this usage – it is greatest when most random, for example – and there are difficult issues about how, in quantum mechanics, such a recondite definition impinges on the critical issue of *what we know*. So we don't have all the answers. But we do have better questions, and that's some kind of progress.

•

You can see that I'm already struggling to find a language that works for talking about these things. That's OK, and you'll have to get used to it. That's how it should be. When words come too easily, it's because we haven't delved deeply enough (you'll see that scientists can be guilty of that too). 'We are suspended in language', said Bohr, who thought more profoundly about quantum mechanics than any of his contemporaries, 'in such a way that we cannot say what is up and what is down.'

It's almost an in-joke that popular accounts of quantum mechanics abound with statements along the lines of 'This isn't a perfect analogy, but . . .' Then what typically follows is a visualization involving marbles and balloons and brick walls and the like. It is the easiest thing in the world for the pedant to say 'Oh, it's not really like that at all.' This isn't my intention. Such elaborately prosaic imagery is often a good place to start the journey, and I will sometimes resort to it myself. Sometimes an imperfect analogy like this is all that can be sensibly expected without engaging in detailed mathematical expositions, and even specialists sometimes have to entertain such pictures if they aren't ready to capitulate to pure abstraction. Richard Feynman did so, and that is good enough for me.

It's only when we abandon those mental crutches, however, that we can start to see why we need to take quantum mechanics more seriously. I don't mean that we should all be terribly earnest about it (Feynman wasn't), but that we should be prepared to be *much more unsettled* about it. I have barely scratched the surface, and *I* am unsettled. Bohr, again, understood this point. He once gave a talk on quantum mechanics to a group of philosophers, and was disappointed and frustrated that they sat and meekly accepted what he said rather than protesting vehemently. 'If a man does not feel dizzy when he first learns about the quantum of action [that is, quantum theory],' said Bohr, 'he has not understood a word.'

I'm suggesting that we don't worry enough about what quantum theory means. I don't mean that we're not interested – it's a peculiar fact that articles about the quirks of quantum theory in popular-science magazines and forums are almost invariably among the most widely read, and there are plenty of accessible books on the subject.* So why complain that we don't worry enough?

Because the issue is often made to seem like 'not *our* problem'. Reading about quantum theory often feels a little like reading anthropology: it tells of a far-off land where the customs are strange. We're comfortable enough about how *our* world behaves; it's this other one that's 'weird'.

That, however, is as parochial, if not quite as offensive, as if I were to assert that the customs of a tribe of New Guinea were 'weird' because they are not mine. Besides, it underestimates quantum mechanics. For one thing, the

---

* Many are excellent, but you could hardly do better than start with Jim Al-Khalili's new 'Ladybird Expert' book *Quantum Mechanics.*

more we understand about it, the more we appreciate how our familiar world is not distinct from it but a consequence of it. What's more, if there is a more 'fundamental' theory underlying quantum mechanics, it seems that it will have to retain the essential features that make the quantum world look so strange to us, extending them into new regimes of time and space. It is probably quantum all the way down.

Quantum physics implies that the world comes from a quite different place than the conventional notion of particles becoming atoms becoming stars and planets. All that happens, surely: but the fundamental fabric from which it sprang is governed by rules that defy traditional narratives. It is another quantum cliché to imply that those rules undermine our ideas of 'what is real' – but this, at least, is a cliché that we might usefully revisit with fresh eyes. The physicist Leonard Susskind is not exaggerating when he says that 'in accepting quantum mechanics, we are buying into a view of reality that is radically different from the classical view'.

Note that: a different view of *reality*, not a different kind of physics. If different physics is 'all' you want, you can look (say) to Einstein's theories of special and general relativity, in which motion and gravity slow time and bend space. That's not easy to imagine, but I reckon you can do it. You just need to imagine time passing more slowly, distances contracting: distortions of your grid references. You can put those ideas into words. In quantum theory, words are blunt tools. We give names to things and processes, but those are just labels for concepts that cannot be properly, accurately expressed in any terms but their own.

A different view of reality, then: if we're serious about that, we're going to need some philosophy. Many scientists, like many of us, take a seemingly pragmatic but rather naïve view of 'reality': it's just the stuff out there that we can see and touch and influence. But philosophers – from Plato and Aristotle through to Hume, Kant, Heidegger and Wittgenstein – have long recognized that this is to take an awful lot for granted that we really should interrogate more closely. Attempts to interpret quantum mechanics demand that interrogation, and so force science to take seriously some questions that philosophers have debated with great depth and subtlety for millennia: What is real? What is knowledge? What is existence? Scientists often have a tendency to respond to such questions with Johnsonian impatience, as though they are either self-evident or useless sophistry. But evidently they are not, and some quantum physicists are now happy to consider what philosophers had and have to say about them. And the field of 'quantum foundations' is the better for it.

•

Are we doomed, though, to be forever 'suspended in language', as Bohr said, not knowing up from down? Some researchers optimistically think that, on the contrary, it might eventually be possible to express quantum theory in terms of – as one of them has put it – 'a set of simple and physically intuitive principles, and a convincing story to go with them'. Wheeler once claimed that if we really understood the central point of quantum theory, we ought to be able to state it in one simple sentence.

Yet there is no guarantee, nor indeed much likelihood, that future experiments are going to strip away all the counter-intuitive aspects of quantum theory and reveal something as concrete, 'commonsensical' and satisfying as the old-style classical physics. Indeed, it is possible that we might *never* be able to say what quantum theory ‘means’.

I have worded that sentence carefully. It’s not exactly (or necessarily) that no one will *know* what the theory means. Rather, we might find our words and concepts, our ingrained patterns of cognition, to be unsuited to articulating a meaning worthy of the name. David Mermin expressed this adeptly when describing how many quantum physicists feel about Niels Bohr himself, who acquired the reputation of a guru with a quasi-mystical understanding that leaves physicists even now poring over his maddeningly cryptic words. ‘I have been getting sporadic flashes of feeling that I may actually be starting to understand what Bohr was talking about’, wrote Mermin:

> Sometimes the sensation persists for many minutes. It’s a little like a religious experience and what really worries me is that if I am on the right track, then one of these days, perhaps quite soon, the whole business will suddenly become obvious to me, and from then on I will know that Bohr was right but be unable to explain why to anybody else.

It might be, then, that all we can ever do is shut up and calculate, and dismiss the rest as a matter of taste. But I think we can do better, and that we should at least aspire to. Perhaps quantum mechanics pushes us to the limits of what we can know and comprehend. Well then, let’s see if we can push back a little.

Quantum mechanics is not

really about the quantum

The temptation to tell quantum mechanics as a historical saga is overwhelming. It's such a great tale. How, at the beginning of the twentieth century, physicists began to realize that the world is constructed quite differently from how they had supposed. How this 'new physics' began to disclose increasingly odd implications. How the founders puzzled, argued, improvised, guessed, in their efforts to come up with a theory to explain it all. How knowledge once deemed precise and objective now seemed uncertain, contingent and observer-dependent.

And the cast! Albert Einstein, Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and other colourful intellectual giants like John von Neumann, Richard Feynman and John Wheeler. Best of all for its narrative value is the largely good-natured but trenchant dispute that rumbled on for decades between Einstein and Bohr about what it all meant – about the nature of reality. This is indeed a superb story, and if you haven't heard it before then you should.*

Yet most popular descriptions of quantum theory have been too wedded to its historical evolution. There is no reason to believe that the most important aspects of the theory are those that were discovered first, and plenty of reason to think that they are not. Even the term 'quantum' is something of a red herring, since the fact that the theory renders a description of the world granular and

---

* I'd recommend beginning with Manjit Kumar's *Quantum* (2008).

particulate (that is, divided into discrete *quanta*) rather than continuous and fluid is more a symptom than a cause of its underlying nature. If we were naming it today, we'd call it something else.

I'm not going to ignore this history. One simply cannot do that when discussing quantum mechanics, not least because what some of the historical doyens had to say on the matter – Bohr and Einstein in particular – remains perceptive and relevant today. But telling quantum theory chronologically can become a part of the problem that we have with it. It yokes us to a particular view of what matters – a view that no longer seems to be looking from the right direction.

•

Quantum theory had the strangest genesis. Its pioneers made it up as they went along. What else could they do? It was a new kind of physics – they couldn't deduce it from the old variety, although they were able nonetheless to commandeer a surprising amount of traditional physics and math. They cobbled old concepts and methods together into new forms that were often nothing much more than a wild guess at what kind of equation or mathematics might do the job.

It is extraordinary how these hunches and suppositions about very specific, even recondite, phenomena in physics cohered into a theory of such scope, precision and power. Far too little is made of this when the subject is taught, either as science or as history. The student is (certainly *this* student was) presented with the mathematical machinery as though it were a result of rigorous deduction and decisive experiment. No one tells you that it often lacks any justification beyond the mere (and obviously important) fact that it works.

Of course, this can't have been sheer luck. The reason Einstein, Bohr, Schrödinger, Heisenberg, as well as Max Born, Paul Dirac, Wolfgang Pauli and others, were able to concoct a mathematical quantum mechanics is that they possessed extraordinary physical intuition informed by their erudition in classical physics. They had amazing instincts for which pieces of conventional physics to use and which to throw away. This doesn't alter the fact that the formalism of quantum theory is makeshift and in the end rather arbitrary. Yes, the most accurate physical theory we possess is something of a Heath Robinson (Americans will say a Rube Goldberg) contraption. Worse than that – for those devices have a clear logic to their operation, a rational connection between one part and another. But most of the fundamental equations and concepts of quantum mechanics are (inspired) guesses.

•

Scientific discovery often starts with an observation or an experiment that no one can explain, and quantum mechanics was like that too. Indeed, the theory could surely not have arisen except from experiment – for there is absolutely no logical reason to expect anything it says. We can't reason ourselves into quantum theory (which, if we believe Jonathan Swift's famous aperçu, presumably means we can never reason ourselves out of it). It is simply an attempt to describe what we see when we examine nature closely enough.

What distinguishes quantum mechanics from other empirically motivated theories, however, is that the quest for underlying causes doesn't allow – at least, hasn't yet allowed – the theory to be constructed from more fundamental ingredients. With any theory, at some point you can't help asking 'So *why* are things this way? Where do these rules come from?' Usually in science you can answer those questions by careful observation and measurement. With quantum mechanics it is not so simple. For it is not so much a theory that one can test by observation and measurement, but a theory about what it means to observe and measure.

Quantum mechanics started as a makeshift gambit by the German physicist Max Planck in 1900. He was studying how objects radiate heat, which seemed like as conventional and prosaic a question as you could imagine a physicist asking. It was, to be sure, a matter of great interest to late-nineteenth-century physicists, but it scarcely seemed likely to require an entire new world view.

Warm objects emit radiation. If they are hot enough, some of that radiation is visible light: they become 'red hot', or with more heating, 'white hot'. Physicists devised an idealized description of this situation in which the emitting object is called a black body – which might sound perverse, but it just means that the object absorbs perfectly all radiation that falls on it. That keeps the issue simple: you only need focus on what gets emitted.

It was possible to make objects that behaved like black bodies – a hole in a warm oven would do the job – and measure how much energy they radiated at different wavelengths of light.* But explaining these measurements in terms of the vibrations within the warm body – the source of the emitted radiation – was no easy matter.

That explanation depended on how heat energy was distributed among the various vibrations. It was a problem for the science called thermodynamics, which describes how heat and energy are moved around. We now identify the vibrations of the black body with the oscillations of its constituent atoms. But when Planck studied the problem in the late nineteenth century there was still no direct evidence for the very existence of atoms, and he was vague about what the 'oscillators' are.

What Planck did seemed so very innocuous. He found that the discrepancy between what thermodynamic theory predicted for black-body radiation and what was seen experimentally could be eased by assuming that the energy of an oscillator can't just have *any* value, but is restricted to chunks of a particular size ('quanta') proportional to the frequency of oscillation. In other words, if an oscillator has a frequency f, then its energy can only take values that are whole-number multiples of f, multiplied by some constant denoted h and now called Planck's constant. The energy can be equal to hf, $2hf$, $3hf$ and so on, but cannot take values in between. This implies that each oscillator can only emit (and absorb) radiation in discrete packets with frequency f, as it moves between successive energy states.

---

* According to classical physics, light is a wave of conjoined electrical and magnetic fields moving through space. The wavelength is the distance between successive peaks. Most light, like sunlight, consists of waves of many different wavelengths, although laser light typically has a very narrow band of wavelengths. This wave view of light was one of the first casualties of quantum theory, as we'll see.

This story is often told as an attempt by Planck to avoid the ‘ultraviolet catastrophe’: the prediction, according to classical physics, that warm bodies should emit ever more radiation as the wavelength gets shorter (that is, closer to the ultraviolet end of visible light’s spectrum). That prediction, which implies – impossibly – that a warm object radiates an infinite amount of energy, follows from the assumption that the heat energy of the object is shared out equally between all its vibrations.

It’s true that Planck’s quantum hypothesis, by supposing that the vibrations can’t just take *any* frequencies, avoids this inconvenient prediction. But that was never his motivation for it. He thought that his new formula for black-body radiation applied only at low frequencies anyway, whereas the ultraviolet catastrophe loomed specifically at high frequencies. The myth probably reflects a sense that quantum theory needed some urgent-sounding crisis to precipitate it. But it didn’t, and Planck’s proposal excited no controversy or disquiet until Albert Einstein insisted on making the quantum hypothesis a general aspect of microscopic reality.

In 1905 Einstein proposed that quantization was a real effect, not just some sleight of hand to make the equations work. Atomic vibrations really do have this restriction. Moreover, he said, it applies also to the energy of light waves themselves: their energy is parcelled up into packets, called photons. The energy of each packet is equal to h times the light’s frequency (how many wave oscillations it makes each second).

Many of Einstein’s colleagues, including Planck, felt that he was taking far too literally what Planck had intended only as a mathematical convenience. But experiments on light and its interactions with matter soon proved Einstein right.

So it was that quantum mechanics seemed at the outset to be about this notion of 'quantized energy': how it increases in steps, not smoothly, for atoms and molecules and light radiation. This, we're told, was the fundamental physical content of the early theory; the rest was added as a theoretical apparatus for handling it. That, however, is a little like saying that Isaac Newton's theory of gravitation was a theory of how comets move through the solar system. It was indeed the appearance of a comet in 1680 that prompted Newton to think about the shape of their paths and to formulate a law of gravity that explained them. But his gravitational theory is not *about* comets. It expresses an underlying principle of nature, of which cometary motion is one manifestation. Likewise, quantum mechanics is not really 'about' quanta: the chunking of energy is a fairly incidental (though initially unexpected and surprising) outcome of it. Quantization was just what alerted Einstein and his colleagues that something was up with classical physics. It was the telltale clue, and no more. We shouldn't confuse the clue with the answer.

Although both Planck and Einstein were rightly rewarded with Nobel Prizes for introducing the 'quantum', that step was simply a historical contingency that set the ball rolling.* Several other experiments in the

---

* The citation for Einstein's 1921 prize was cautiously worded, acknowledging how his work had helped to understand a phenomenon called the photoelectric effect, which drew on the notion of light quanta. At that point, the full implications for quantum theory were still considered too speculative to be granted such credit. Einstein was actually awarded the prize in 1922, since the 1921 prize was deferred for a year in the absence of nominations that were deemed worthy.

1920s and 30s could equally have kick-started quantum theory, had it not already been launched.

Put it this way: grant the rules of quantum mechanics and you must get quantization, but the reverse is not true. Quantization of energy could, in itself, conceivably be a phenomenon of classical physics. Suppose that nature just happens to be constructed in such a way that, at the smallest scales, energies have to be quantized: restricted to discrete values in a staircase of possibilities. That's surprising – we don't seem to have any reason to expect it (although it turns out to explain a lot of our direct experience, such as why grass is green) – but hey, why not? This could have been the end of the matter: nature is grainy at small scales. Einstein would have been happy with that.

The best illustration I know of that quantization is rather incidental to quantum theory is found in the book *Quantum Mechanics: The Theoretical Minimum*, based on a series of lectures that Leonard Susskind, a professor of theoretical physics at Stanford University, gave to undergraduates, which were written up with the help of the writer Art Friedman. The book is described as being 'for anyone who ever regretted not taking physics at university, who knows a little but would like to know more'. That's a rather optimistic assessment, but with a reasonable level of math you could learn all you needed to know in this marvellous tract about the theory. With that aim in mind, Susskind has organized the material so as to tell you what you need to know in the order that you need to know it, in distinction from the common practice of introducing topics and concepts in more or less chronological order. When, then, do you learn about quantization of Planck's 'oscillators'? In the last chapter. In fact 'The Importance of Quantization' is the last section of that final chapter. That's how modern physics judges the *conceptual* significance of Planck's hypothesis, and it's a fair assessment.

•

So if you want to understand what quantum mechanics is really about, what *do* you start with? Susskind's Lecture 1 is 'Systems and Experiments'. Here Susskind explains what is fundamentally different between quantum and classical mechanics. And it's *not* (as is often implied too) that quantum works at small scales and classical at big ones.

Practically speaking, that often *is* the difference, but only because, as we will see later, by the time objects get as big as tennis balls, quantum rules have conspired to generate classical behaviour. The significance of the size difference is not in terms of what objects do, but in terms of our perceptions. Because we haven't evolved to perceive quantum behaviour except in its limiting form of classical behaviour, we've had no grounds to develop an intuition for it. At least, that is probably part of the story; there may be more to it, as we'll also see.

The key distinctions between classical mechanics and quantum mechanics, in Susskind's view, are these:

- Quantum physics has 'different abstractions' – how objects are represented mathematically, and how those representations are logically related.
- Quantum physics has a different relationship between the state of a system and the result of a measurement on that system.

Don't worry about the first of these yet; regard it as analogous to saying that the concepts we use in physics are different from those we use in, say, literary theory or macroeconomics. It's no big deal.

You should worry about the second, though. In a sense, all of quantum theory's counter-intuitive nature (I am trying very hard not to call it weirdness) is packaged up here.

What does it mean to talk about the relationship between the state of a system and a measurement on the system? It's an odd phrase, and that's because this relationship is usually so trivial that we don't even think about it. If a tennis ball is in the state of travelling through the air at 100 mph, and I measure its speed, then that is the value I measure. A measurement tells us about the state of the ball's motion. Of course, there are limits of accuracy – I might have to say that the speed is 100 ± 1 mph – but that's just an instrumental issue. I could probably do better.

So we have no problem saying that the tennis ball was travelling at 100 mph and then I measured it. The tennis ball had the pre-existing property of a speed of 100 mph, which I could determine by measurement. We would never think of saying that it was travelling at 100 mph *because* I measured it. That wouldn't make any sense.

In quantum theory, we do have to make statements like that. And then we can't help asking what it means. That's when the arguments start.

Later we'll see some of the concepts that have been developed to talk about this problem of measurement – of the relationship between the state of a quantum system and what we observe of it. We'll hear about the talismanic conceptual paraphernalia of quantum theory: wavefunctions, superposition, entanglement and so forth. But these are all just handy tools that enable us to make predictions about what a measurement will show us, which is by and large the goal of fundamental science.

That Susskind's second principle – the relationships between states and measurements – can be put into words, without any need for equations or fancy jargon, should reassure us. It's not easy to understand what the words mean, but they reflect the fact that the most fundamental message of quantum theory isn't a purely mathematical one.

Some physicists might be tempted to argue precisely the opposite: that the math *is* the most fundamental description. They might say this basically because the math makes perfect sense whereas the words don't quite. But that would be to make a semantic error: equations purportedly about physical reality are, without interpretation, just marks on paper. We can't hide behind equations from that 'not quite' – not if we truly want to derive *meaning*. Feynman knew this.

Susskind's second principle is really a statement about our active involvement with the world as we seek knowledge about it. *That* – which has been the bedrock of philosophy for over two millennia – is where we must look for meaning.

Quantum objects are
particle (but sometimes

neither wave nor
they might as well be)

One of the problems in talking about quantum objects is deciding what to call them. It seems like a trivial point, but actually it's fundamental.

'Quantum objects' is terribly clunky, and vague too. What's wrong with 'particle'? When we speak of electrons and photons, atoms and molecules, it seems perfectly reasonable to use that word, and I'll occasionally do so. Then we might have the image of a tiny little *thing*, a microscopic ball-bearing all hard and shiny. But probably the most widely known fact of quantum mechanics is that 'particles can be waves'. What then becomes of our compact little balls?

We could simply give these quantum things a new name: quantons, say, which by definition can show wave-like or particle-like behaviour. But there is more than enough jargon in this subject already, and replacing familiar, comfortable words with neologisms that seem designed only to sweep complications under the carpet doesn't feel terribly satisfactory. So for the present purposes, 'objects' and 'particles' will have to do. Except, I suppose, when they're like waves.

The notion of wave–particle duality goes back to the earliest days of quantum mechanics, but it is as much an impediment as it is a crutch to our understanding. Einstein expressed it by saying that quantum objects present us with a choice of languages, but it's too easily forgotten that this is *precisely* what it is: a struggle to formulate the right words, not a description of the reality behind them. Quantum objects are not sometimes particles and sometimes waves, like a football fan changing her team allegiance according to last week's results. Quantum objects are what they are, and we have no reason to suppose that 'what they are' changes in any meaningful way depending on how we try to look at them. Rather, all we can say is that what we measure sometimes looks like what we would expect to see if we were measuring discrete little ball-like entities, while in other experiments it looks like the behaviour expected of waves of the same kind as those of sound travelling in air, or that wrinkle and swell on the sea surface. So the phrase 'wave–particle duality' doesn't really refer to quantum objects at all, but to the interpretation of experiments – which is to say, to our human-scale view of things.

•

In 1924 the French physicist and aristocrat Louis de Broglie proposed that quantum particles – then still envisaged as tiny lumps of *stuff* – might display wave-like properties. His idea was, like so many others in early quantum theory, nothing much more than a hunch. He was generalizing from, indeed inverting, Einstein's earlier argument that light waves display particle-like behaviour when they manifest as photons with discrete energies.

If light waves can be particle-like, de Broglie said in his doctoral thesis, then might not the entities we've previously considered as particles (such as electrons) be wavy? The proposal was controversial and all but dismissed until Einstein suggested, after some reflection, that it was worth heeding after all. 'It looks completely crazy,' he wrote, 'but it's a completely sound idea.'

De Broglie didn't develop his idea into a full-blown theory. But there was already a mature mathematical theory of classical waves; maybe we could use that to describe the alleged waviness of particles? That's just what Erwin Schrödinger, a professor of physics at Zurich, did. After being given de Broglie's thesis and challenged to describe wave-like particles in formal terms, he wrote down an expression for how they might behave.

It was not quite like an ordinary wave equation of the sort used to describe water waves or sound waves. But it was mathematically very similar.

Why *wasn't* it identical? Schrödinger didn't explain his reason, and it now seems clear that he didn't exactly have one. He simply wrote down what he thought a wave equation for a particle such as an electron ought to look like. That he seems to have made such a good guess is even now rather extraordinary and mysterious. Or to put it another way: Schrödinger's wave equation, which is now a part of the core conceptual machinery of quantum mechanics, was built partly by intuition and imagination, albeit combined with a deeply informed sense of which parts of classical physics it was appropriate to commandeer. It can't be proved, but only inferred by analogy and good instinct. This doesn't mean that the equation is wrong or untrustworthy; but its genesis shows how creativity in science depends on more than cold reason.

Wave equations stipulate what the *amplitude* of the wave is in different parts of space. For a water wave, the amplitude is simply how high the water surface is. For a sound wave, it means how strongly the air is compressed in the peaks of the wave, and how severely it is 'stretched' or rarefied in the troughs. Pick a spot in space and you'll