Praise for

THROUGH TWO DOORS AT ONCE

"A fascinating tour through the cutting-edge physics the experiment keeps on spawning."

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"*Through Two Doors at Once* offers beginners the tools they need to seriously engage with the philosophical questions that likely drew them to quantum mechanics."

—*Science*

"At a time when popular physics writing so valorizes theory, a quietly welcome strength of Ananthaswamy's book is how much human construction comes into focus here. This is not 'nature' showing us, but us pressing 'nature' for answers to our increasingly obsessional questions."

—Margaret Wertheim, *The Washington Post*

"A thrilling survey of the most famous, enduring, and enigmatic experiment in the history of science."

—*Kirkus Reviews*, starred review

"Following up 2015's acclaimed *The Man Who Wasn't There*, Ananthaswamy treats a nineteenth-century light experiment as a sprawling intellectual adventure story. . . . This accessible, illuminating book shows that no matter how sophisticated the lab setup, the double-slit experiment still challenges physicists."

—*Publishers Weekly*, Top 10 Science Books for Fall 2018

"An excellent and comprehensive exploration of notable double-slitlike experiments."

—Forbes.com

"An engaging and accessible history of a fascinating and baffling

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THROUGH TWO DOORS AT ONCE

Prologue

THE STORY OF NATURE TAUNTING US

The office is simply the most uncluttered of any physicist's office I have ever seen. There's a chair alongside a small table, with nothing on it. No books, no papers, no lamp, no computer, nothing. A sofa graces the office. Large windows overlook a small lake, the trees around which are bare, except for a few stragglers that are holding on to their fall foliage, defying the approaching winter in this part of Ontario, Canada. Lucien Hardy puts his laptop on the table—pointing out that he does most of his work in cafés and figures that all he needs in his office is a café-like small table to set down his laptop.

There is the obligatory blackboard, taking up most of one wall of his office. It doesn't take long for Hardy to spring up and start chalking it up with diagrams and equations—something that most of the quantum physicists I meet seem inclined to do.

We start talking about some esoteric aspect of quantum physics, when he stops and says, "I started off the wrong way." To reset our discussion, he says, "Imagine you have a factory and they make bombs." He has my attention.

He writes two names on the blackboard: Elitzur and Vaidman. He is talking about something called the Elitzur-Vaidman bomb puzzle. Named after two Israeli physicists, the puzzle exemplifies the counterintuitive nature of the quantum world in ways that nonphysicists can appreciate. It confounds physicists too in no small measure.

The problem goes something like this. There's a factory that makes bombs equipped with triggers. The triggers are so sensitive that a single particle, any particle, even a particle of light, can set them off. There's a big dilemma, however. The factory's assembly line is faulty. It's churning out both good bombs with triggers and bad bombs without triggers. Hardy writes them as "good" and "bad" and quips about the quotation marks: "Obviously, you may have a different moral perspective on it."

The task is to identify the good bombs. This means having to check whether the bombs have triggers. But examining each bomb isn't the correct strategy, because in order to do so, you'd need to shine light on it, however faint, and that would cause a good bomb to explode. The only ones left unexploded would be the duds without triggers.

So, how does one solve this problem? If it helps, we are allowed one concession: we can detonate some bombs, as long as we are left with some good, undetonated bombs.

From our everyday experience of how the world works, this is an impossible problem to solve. But the quantum world—the world of very small things like molecules and atoms and electrons and protons and photons—behaves in bizarre ways. The physics that governs the behavior of this microscopic world is called quantum physics or quantum mechanics. And we can use quantum physics to find good bombs without setting them off. Even with a simple setup, it's possible to salvage about half the good bombs. It involves using a modern variation of a 200-year-old experiment.

Called the double-slit experiment, it was first done in the early 1800s to challenge Isaac Newton's ideas about the nature of light. The experiment took center stage again in the early twentieth century, when two of the founders of quantum physics, Albert Einstein and Niels Bohr, grappled with its revelations about the nature of reality. In the 1960s, Richard Feynman extolled its virtues, saying that the double-slit experiment contained all of the mysteries of the quantum world. A simpler and more elegant experiment would be hard to find, the workings of which a high school student can grasp, yet profound enough in its implications to bewilder brains like Einstein's and Bohr's, a confusion that continues to this day.

This is the story of quantum mechanics from the perspective of one classic experiment and its subtle, sophisticated variations (including one that, as we'll see, solves the Elitzur-Vaidman bomb puzzle), whether these variations are carried out as thought experiments by luminous minds or painstakingly performed in the basement labs of physics departments. It's the story of nature taunting us: catch me if you can.

1

THE CASE OF THE EXPERIMENT WITH TWO HOLES

Richard Feynman Explains the Central Mystery

> There is nothing more surreal, nothing more abstract than reality.
>
> **—Giorgio Morandi**

Richard Feynman was still a year away from winning his Nobel Prize. And two decades away from publishing an endearing autobiographical book that introduced him to non-physicists as a straight-talking scientist interested in everything from cracking safes to playing drums. But in November 1964, to students at Cornell University in Ithaca, New York, he was already a star and they received him as such. Feynman came to deliver a series of lectures. Strains of “Far above Cayuga’s Waters” rang out from the Cornell Chimes. The provost introduced Feynman as an instructor and physicist par excellence, but also, of course, as an accomplished bongo drummer. Feynman strode onto the stage to the kind of applause reserved for performing artists, and opened his lecture with this observation: “It’s odd, but in the infrequent occasions when I have been called upon in a formal place to play the bongo drums, the introducer never seems to find it necessary to mention that I also do theoretical physics.”

By his sixth lecture, Feynman dispensed with any preamble, even a token “Hello” to the clapping students, and jumped straight into how our intuition, which is suited to dealing with everyday things that we can see and hear and touch, fails when it comes to understanding nature at very small scales.

And often, he said, it's experiments that challenge our intuitive view of the world. "Then we see unexpected things," said Feynman. "We see things that are very far from what we could have imagined. And so our imagination is stretched to the utmost —not, as in fiction, to imagine things which aren't really there. But our imagination is stretched to the utmost just to comprehend those things which are there. And it's this kind of a situation that I want to talk about."

The lecture was about quantum mechanics, the physics of the very small things; in particular, it was about the nature of light and subatomic bits of matter such as electrons. In other words, it was about the nature of reality. Do light and electrons show wavelike behavior (like water does)? Or do they act like particles (like grains of sand do)? Turns out that saying yes or no would be both correct and incorrect. Any attempt to visualize the behavior of the microscopic, subatomic entities makes a mockery of our intuition.

"They behave in their own inimitable way," said Feynman. "Which, technically, could be called the 'quantum-mechanical' way. They behave in a way that is like nothing that you have ever seen before. Your experience with things that you have seen before is inadequate—is incomplete. The behavior of things on a very tiny scale is simply different. They do not behave *just* like particles. They do not behave *just* like waves."

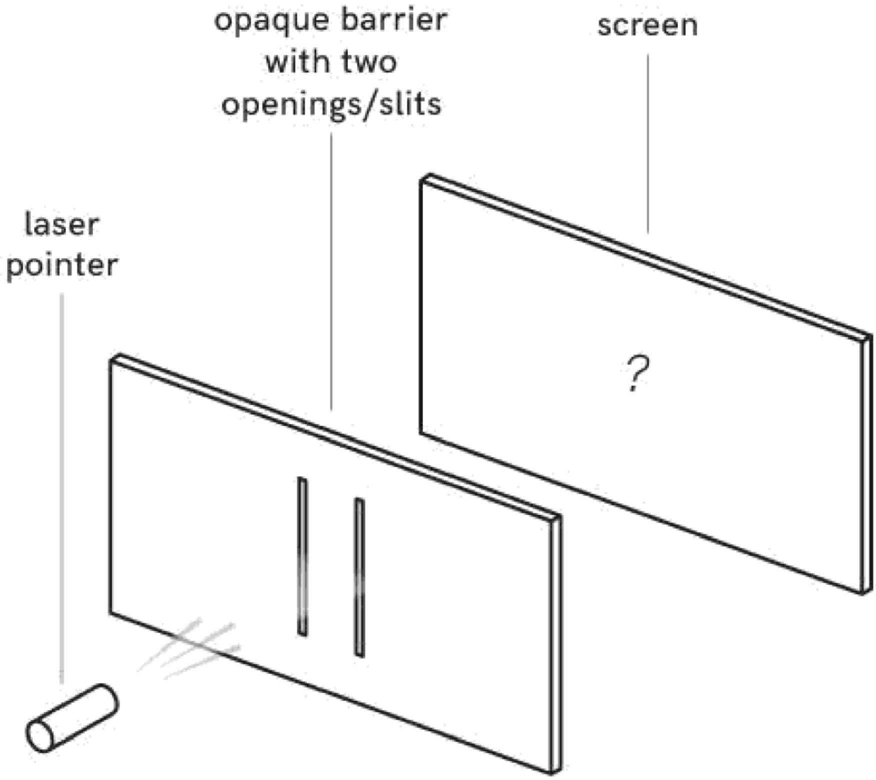
But at least light and electrons behave in "exactly the same" way, said Feynman. "That is, they're both screwy."

Feynman cautioned the audience that the lecture was going to be difficult because it would challenge their widely held views about how nature works: "But the difficulty, really, is psychological and exists in the perpetual torment that results from your saying to yourself 'But how can it be like that?' Which really is a reflection of an uncontrolled, but I say utterly vain, desire to see it in terms of some analogy with something familiar. I will not describe it in terms of an analogy with something familiar. I'll simply describe it."

And so, to make his point over the course of an hour of spellbinding oratory, Feynman focused on the "one experiment which has been designed to contain all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature."

It was the double-slit experiment. It's difficult to imagine a simpler experiment—or, as we'll discover over the course of this book, one more confounding. We start with a source of light. Place in front of the source a sheet of opaque material with two narrow, closely spaced slits or openings. This creates two paths for the light to go through. On the other side of the opaque sheet is a screen. What would you expect to see on the screen?

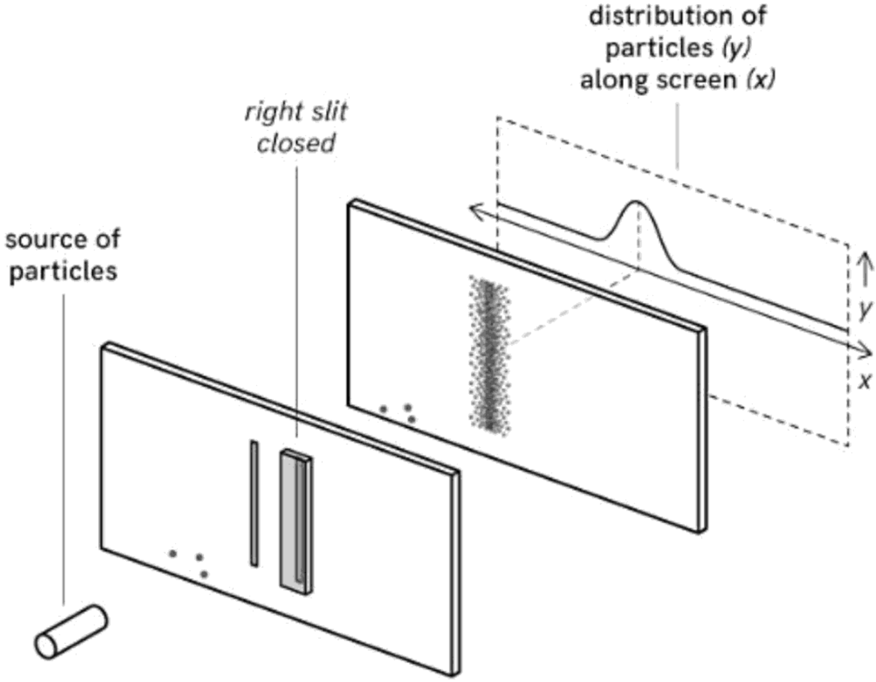
The answer, at least in the context of the world we are familiar with, depends on what one thinks is the nature of light. In the late seventeenth century and all of the eighteenth century, Isaac Newton's ideas dominated our view of light. He argued that light was made of tiny particles, or "corpuscles," as he called them. Newton's "corpuscular theory of light" was partly formulated to explain why light, unlike sound, cannot bend around corners. Light must be made of particles, Newton argued, since particles don't curve or bend in the absence of external forces.

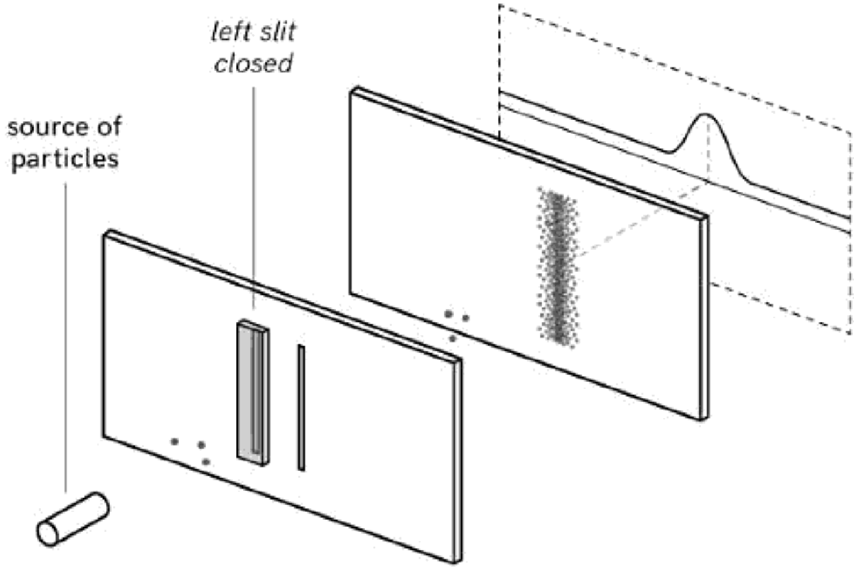


In his lecture, when Feynman analyzed the double-slit experiment, he first considered the case of a source firing particles at the two slits. To accentuate the particle nature of the source, he urged the audience to imagine that instead of subatomic particles (of which electrons and particles of light would be examples), we were to fire bullets from a gun—which "come in lumps." To avoid too much violent imagery (what with bombs in the prologue, and a thought experiment with gunpowder to come), let's imagine a source that spews particles of sand rather than bullets; we know that sand comes in lumps, though the lumps are much, much smaller than bullets.

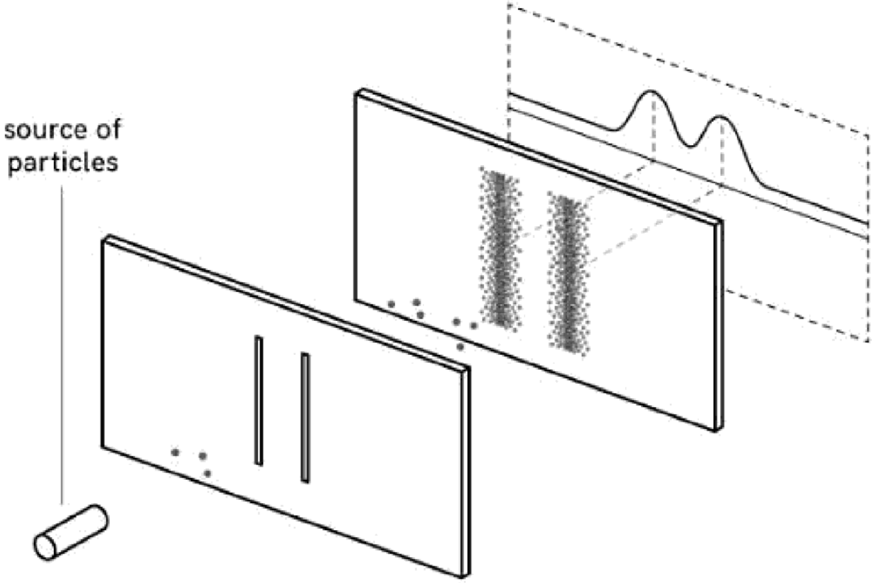
First, let's do the experiment with either the left slit or the right slit closed. Let's take it that the source is firing grains of sand at high enough speeds that they have straight trajectories. When we do this, the grains of sand that get through the slits mostly hit the region of the screen directly behind the open slit, with the numbers tapering off on either side. The higher the height of the graph, the more the number of grains of sand reaching that location on the screen.

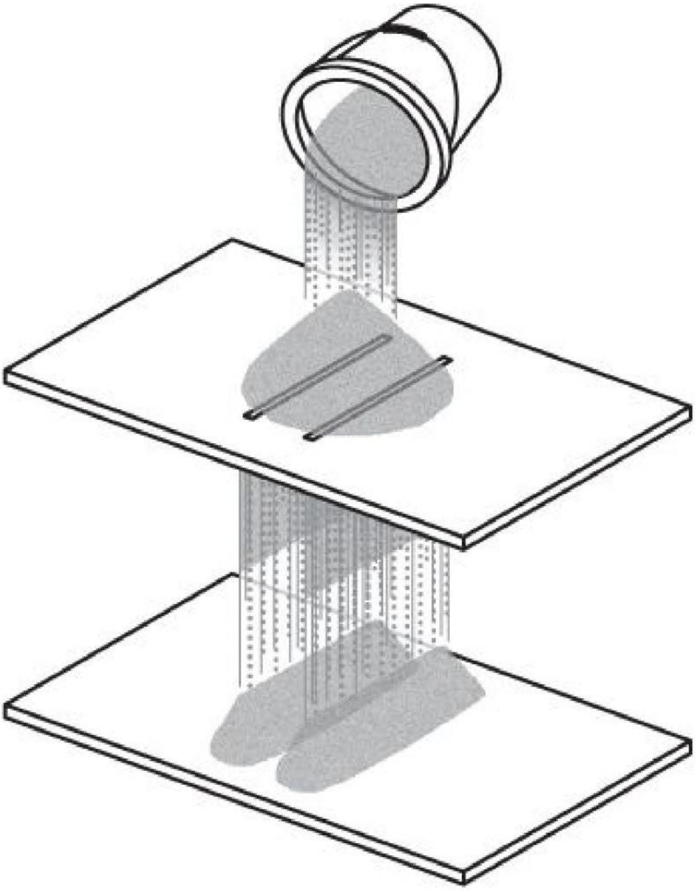
Now, what should we see if both slits are open? As expected, each grain of sand passes through one or the other opening and reaches the other side. The distribution of the grains of sand on the far screen is simply the sum of what goes through each slit. It's a demonstration of the intuitive and sensible behavior of the nonquantum world of everyday experience, the classical world described so well by Newton's laws of motion.





To be convinced that this is indeed what happens with particles of sand, let's orient the device such that the sand is now falling down onto the barrier with two slits. Our intuition clearly tells us that two mounds should form beneath the two openings.





Turning the experiment back to its original position, let's dispense with the sand and consider a source that's emitting light, and assume that light's made of Newtonian corpuscles. Informed by our experiment with sand particles, we'd expect to see two strips of light on the screen, one behind the right slit and one behind the left slit, each strip of light fading off to the sides, leading to a distribution of light that is simply the sum of the light you'd get passing through each slit.

Well, that's not what happens. Light, it seems, does not behave as if it's made of particles.

Even before Newton's time, there were observations that challenged his theory of the particle nature of light. For example, light changes course when going from one medium to another—say, from air to glass and back into air (this phenomenon, called refraction, is what allows us to make optical lenses). Refraction can’t be easily explained if you think of light as particles traveling through air and glass, because it requires positing an external force to change the direction of light when it goes from air to glass and from glass to air. But refraction can be explained if light is thought of as a wave (the speed of the wave would be different in air than in glass, explaining the change in direction as light goes from one type of material to another). This is exactly what Dutch scientist Christiaan Huygens proposed in the 1600s. Huygens argued that light is a wave much like a sound wave, and since sound waves are essentially vibrations of the medium in which they are traveling, Huygens argued that light too is made of vibrations of a medium called ether that pervades the space around us.

This was a serious theory put forth by an enormously gifted scientist. Huygens was a physicist, astronomer, and mathematician. He made telescopes by grinding lenses himself, and discovered Saturn’s moon Titan (the first probe to land on Titan, in 2005, was named Huygens in his honor). He independently discovered the Orion nebula. In 1690, he published his *Traité de la Lumière* (*Treatise on Light*), in which he expounded his wave theory of light.

Newton and Huygens were contemporaries, but Newton’s star shone brighter. After all, he had come up with the laws of motion and the universal law of gravitation, which explained everything from the arc of a ball thrown across a field to the movement of planets around the sun. Besides, Newton was a polymath of considerable renown (as a mathematician, he gave us calculus, and even ventured into chemistry, theology, and writing biblical commentaries, not to mention all his work in physics). It was no wonder that his corpuscular theory of light, despite its shortcomings, overshadowed Huygens’s ideas of light being wavelike. It’d take another polymath to show up Newton when it came to understanding light.

Thomas Young has been called “The Last Man Who Knew Everything.” In 1793, barely twenty years of age, he explained how our eyes focus upon objects at different distances, based partly on his own dissection of an ox's eyes. A year later, on the strength of that work, Young was made a Fellow of the Royal Society, and in 1796 he became "doctor of physic, surgery, and midwifery." When he was in his forties, Young helped Egyptologists decipher the Rosetta stone (which had inscriptions in three scripts: Greek, hieroglyphics, and something unknown). And in between becoming a medical doctor, getting steeped in Egyptology, and even studying Indo-European languages, Young delivered one of the most intriguing lectures in the history of physics. The venue was the Royal Society of London, and the date, November 24, 1803. Young stood in front of that august audience, this time as a physicist describing a simple and elegant homespun experiment, which, in his mind, had unambiguously established the true nature of light and proved Newton wrong.

"The experiments I am about to relate . . . may be repeated with great ease, whenever the sun shines," Young told the audience.

Whenever the sun shines. Young wasn't overstating the simplicity of his experiment. "I made a small hole in a window-shutter, and covered it with a piece of thick paper, which I perforated with a fine needle," he said. The pinhole let through a ray of light, a sunbeam. "I brought into the sunbeam a slip of card, about one-thirtieth of an inch in breadth, and observed its shadow, either on the wall, or on other cards held at different distances."

If light is made of particles, Young's "slip of card" would have cast a sharp shadow on the wall in front, because the card would have blocked some of the particles. And if so, Newton would have been proved right.

If, however, light is made of waves, as Huygens claimed, then the card would have merely impeded the waves, like a rock impedes flowing water, and the wave would have gone around the card, taking two paths, one on either side of the card. The two paths of light would eventually recombine at the wall opposite the window shutter to create a characteristic pattern: a row of alternating bright and dark stripes. Such stripes, also known as interference fringes, are created when two waves overlap.

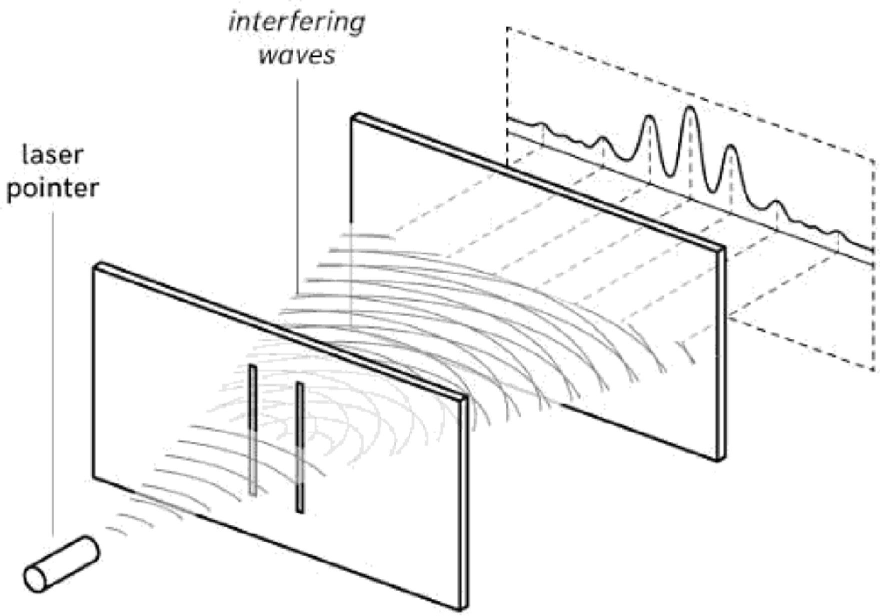
Crucially, the central fringe would be bright, exactly where you'd expect a dark shadow if light were made of particles.

We know about interference from our everyday experience of waves of water. Think of an ocean wave hitting two openings in a coastal breakwall. New waves emerge from each opening (a process called diffraction) and travel onward, where they overlap and interfere with each other. In regions where the crests of both waves arrive at the same time, there's constructive interference and the water is at its highest (analogous to bright fringes of light); and in regions where the crest from one wave arrives at the same time as the trough of the other, the waves cancel each other out and there's destructive interference (corresponding to dark fringes).

Young saw such optical interference fringes. Specifically, since he was working with sunlight, which contains light of all colors, he saw a central region that was flanked by fringes of colors. The central region, upon closer inspection, was seen to be made of light and dark fringes. The numbers of these fringes and their widths depended on how far away the pinhole in the window shutter was from the screen or wall. And the middle of the central region was always white (a bright fringe). He had shown that light is wavelike.

There must have been disbelief in the audience, for Young was going against Newton's ideas. Even before Young's lecture, articles written anonymously in the *Edinburgh Review* had been heavily critical of his work. The author, who turned out to be a barrister named Henry Brougham (he became Lord Chancellor of England in 1830), was scathing, calling Young's work "destitute of every species of merit" and "the unmanly and unfruitful pleasure of a boyish and prurient imagination."

It was anything but. Soon enough, Young's ideas got further support from other physicists. His experiment led to what's now called the double-slit experiment and was in fact the first formulation of it—the very same experiment whose virtues Feynman extolled during his lecture at Cornell. In the more standard doubleslit experiment, Young's sunbeam is replaced by a source of light. And instead of a "slip of card" placed in the sunbeam's path to create two paths for the light, the double-slit experiment creates two paths of light by letting the light fall on an opaque barrier with two narrow slits or openings through which the light can pass. And on the screen on the far side, you see an interference pattern, essentially fringes similar to what Young saw on the wall opposite the window shutter (if the screen is a photographic plate, or a piece of glass coated with photosensitive material, then the image can be thought of as a film negative: dark regions will form where the film is being exposed to light). You don't see just two strips tapering away, which you'd expect if light behaved as if it came in lumps. It's behaving like a wave.

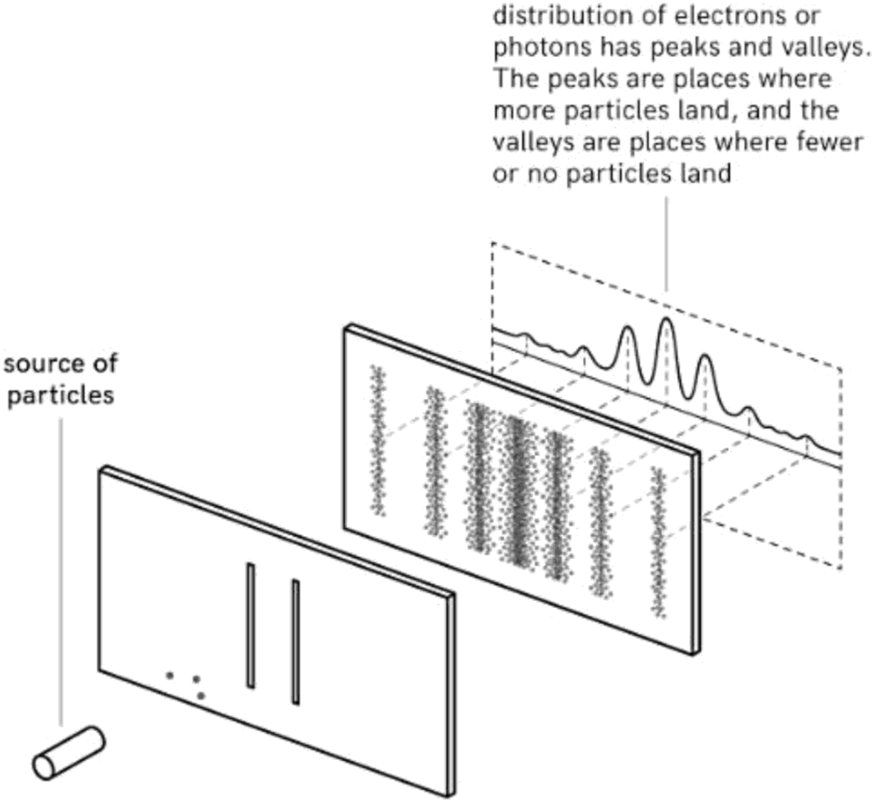


So, well before quantum physics was even a gleam in anyone's eyes, Young had seemingly settled the debate between Newton and Huygens (despite skeptics who continued to favor Newton). Young came down in favor of Huygens's light-is-a-wave idea. And so things stood until the quantum revolution.

The revolution began with bewildering discoveries in the early 1900s, including Albert Einstein's 1905 assertion that light should be thought of as being made of particles, because it was the only way to explain a phenomenon known as the photoelectric effect (which helps us convert sunlight into electricity, giving us the technology of solar panels). These particles of light came to be called photons. For any given frequency or color of light, a photon of light is the smallest unit of energy, and it cannot be divided any further: the light cannot come with any less energy than contained in one photon. Einstein's argument is somewhat involved, but for now, if we accept the idea that there are certain situations in physics where you have to treat light as made of particles, then the double-slit experiment starts challenging our intuitive sense of reality.

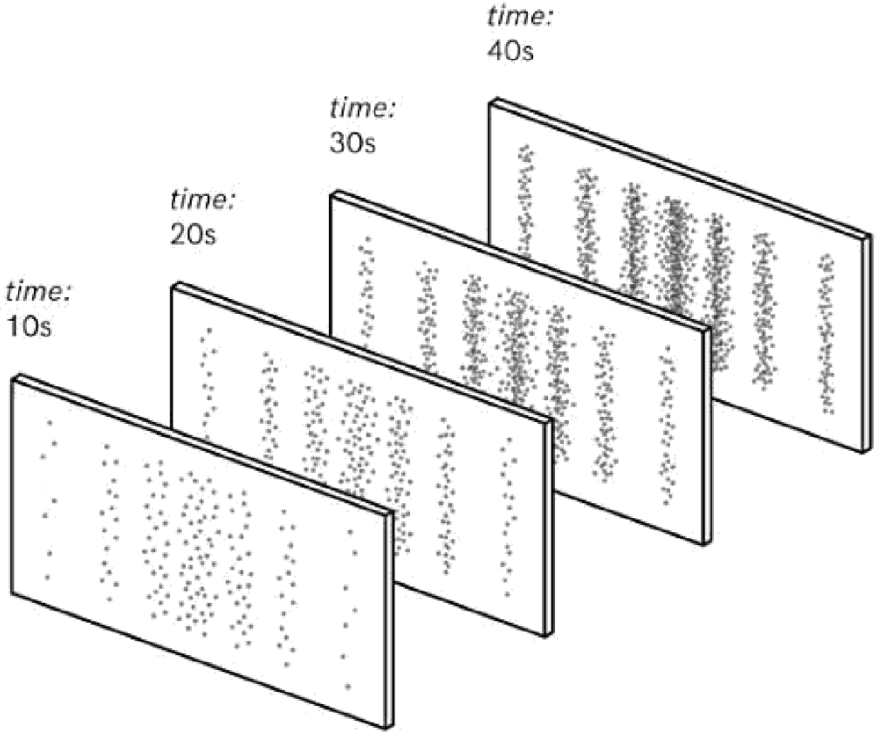
Feynman spoke of the double-slit experiment as embodying the "central mystery" of quantum mechanics. To show why, he replaced the gun shooting bullets (or, in our case, grains of sand) with a source of electrons. Everyone in the 1960s knew that electrons came in lumps. They are one of the many types of elementary particles that make up the subatomic world, including photons. We'll use photons instead of electrons. The fact that the experiment, its results, and its implications don't change whether we are using photons, which are particles of light without any mass, or electrons, which are particles of matter with some mass, leads to its own set of mystifying questions. As Feynman said, both are screwy in the same way.

Here's what happens if you use photons. Unlike what we got with particles of sand, you don't get two bands of light on the screen. Instead, you get fringes, similar to the interference pattern that Young observed, suggesting that photons are behaving like waves. To get a sharply defined set of fringes, it's best to use light of one color. So the source can be, say, streaming out an intense beam of photons of red light that pass through the double slit.



When both slits are open, you get the interference pattern, suggesting that light (which we know now is made of particles) is going through both slits. But if you close one of the two slits (doesn't matter which one), the interference pattern disappears, clearly suggesting that light is going through only one slit and there's nothing for it to interfere with.

The experiment, however, really starts messing with our minds when we consider a source that emits one photon at a time. We'll come to the ways in which physicists invented sources to do that. It wasn't possible in 1964, when Feynman was giving his lecture. For now, let's assume we have such a source in hand. If so, each photon goes through the apparatus, and we make sure there's only one photon passing through the setup at a time. The photon hits the photographic plate on the far side and creates a spot. If we let enough spots accumulate, our intuition says that these photons should act like grains of sand and line up behind each slit. There should be no interference pattern.



We'd be wrong. As it happens, even though each photon seems to be landing at some random position, fringes emerge when enough photons have made their mark on the photographic plate. Each photon makes a dark spot on the plate; places where the photons mostly land become dark stripes, and fringes build up over time.

This is somewhat curious. It's clear that we can get an interference pattern when one wave interferes with another. But our photons are going through the apparatus one by one. There's no interference between one photon and the next, or the first photon and the tenth, and so on. Each photon is on its own. Nonetheless, each photon is mostly landing on the photographic plate at those positions that eventually become regions of constructive interference and mostly avoiding those places that become regions of destructive interference. We get interference fringes. It's *as if* each photon is exhibiting wavelike behavior, *as if* it's interfering with itself.

This is happening even though we create each photon as a particle, and detect it on a photographic plate as a particle: the results *seem to* suggest that between the creation and detection, each particle acts like a wave, and somehow goes through both slits simultaneously. How else do you explain the interference pattern?

If that's not mysterious enough, consider what happens if we try to find out which slit a photon goes through (our intuition, after all, says that it surely went through just one slit, not both). Say you have a mechanism for detecting the passage of a photon through one or the other slit without destroying the photon. If you do that, the interference pattern goes away (meaning the photon stops behaving like a wave and starts acting like a particle)—and you get a pattern that's simply the sum of the "lumps" going through each slit. Stop trying to sneak a peek at the photon's path and it goes back to behaving like a wave—the interference pattern reemerges.

There's yet another way to appreciate this mystery. When you are not looking at the photons' paths, individual photons almost never go to certain places on the photographic plate—the places that eventually become regions of destructive interference. But if you start monitoring their paths, they will go to the very locations that they otherwise shun. What's going on?

The curious behavior continues. If you were to fire grains of sand at the double slit, and if you knew everything about the initial conditions of each grain of sand (its initial velocity, the angle at which it leaves the sand gun, etc.), you can predict using Newton's laws exactly where the grain of sand will end up on the screen opposite the double slit, taking into account any deflections due to the interaction with the slits. This is how physics is supposed to work. But you can't do that with photons (or electrons, or anything quantum mechanical for that matter).

Even if you have all the information about a single photon as it leaves the source and goes toward the double slit, you can only calculate the probability of the photon landing on a certain part of the photographic plate. For example, the photon could land at any one of the many regions of constructive interference—but there's no way to tell exactly where any particular photon will go. Nature, at its deepest, seems inherently nondeterministic. Or is it merely hiding its secrets, and we haven't dug deep enough yet?

The questions pile up. Between the production of the photon and its eventual detection, both proofs of its particle nature, the photon ostensibly behaves like a wave if we choose not to look at which path it takes, and as a particle otherwise. Does the photon "know" we are looking at its wave nature or particle nature? If so, how? And can we fool the photon, say, by not revealing our hand until it has crossed the double slit as a wave, and only then choosing to see which slit it went through, thus examining its particle-like behavior?

Maybe there is a simpler answer: that the photon is always a particle and always goes through one or the other slit. And something else, something that our standard theories don't account for, goes through both slits to produce the wavelike behavior. In that case, what is that something?

If it crossed your mind that human consciousness is somehow involved in causing the photon to behave one way or the other, you wouldn't be alone in thinking so. As often happens when confronted with two mysteries (in this case the odd behavior of the quantum world and the inexplicable nature of consciousness), it's almost human nature to want to conflate the two.

It'd be twenty years on from Feynman's lecture at Cornell that the double-slit experiment would be done using single photons. It was an example of how, from Young's efforts in the early 1800s to modern versions, physicists continue to use the double-slit experiment to understand the nature of reality. The experiment hasn't changed in its conceptual simplicity for more than two hundred years, but it has become technologically more and more sophisticated, as experimenters keep thinking of clever ways to trick nature into revealing its profoundest secrets.

2

WHAT DOES IT MEAN “TO BE”?

The Road to Reality, from Copenhagen to Brussels

> The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them . . . is impossible.
>
> **—Werner Heisenberg**

Quantum physics has been with us for about a century. But for almost two centuries before the birth of quantum physics, our ideas of how nature works were governed by laws discovered by Isaac Newton. He elucidated his laws in the *Principia*, an astonishing treatise published in 1687. Crucial to the Newtonian conception of nature was that it was made of particles of matter whose dynamics were governed by the forces acting upon them, including the mutually attractive force of gravity. Light too was regarded as having particle nature, though this was debated. Huygens, Young, and others challenged this, arguing for light’s wave nature. So, while the Newtonian universe was one of particles of matter, light stood apart, its place in the categories of things that make up the world—the ontology of the world—somewhat unclear.

A French prince and physicist, Louis de Broglie, centuries later, would recount this time in the history of physics rather eloquently: “When Light reaches us from the sun or the stars it comes to the eye after a journey across vast spaces void of Matter.

It follows from this that Light can cross empty space without difficulty . . . it is not bound up with any motion of Matter. Hence a description of the physical world would remain incomplete unless we were to add to Matter another reality independent of it. This entity is Light. Now what is Light? What is its structure?"

As de Broglie wrote, such questions were looming large in the 1860s, when Scottish scientist James Clerk Maxwell developed the mathematical foundation for physicists to start thinking of light as a wave.

Maxwell's work first involved unifying electricity and magnetism, which until then had been viewed as separate forces, into one force. Building on earlier work by the English physicist and chemist Michael Faraday, Maxwell came up with a theory combining electricity and magnetism, and predicted that they move as one electromagnetic wave. He presented these ideas on December 8, 1864, to the Royal Society of London. The ontology of nature had changed. In addition to particles, it now included electromagnetic fields—oscillations of energy—that moved at the speed of light. Particles were localized, but fields were diffuse and could spread and exert an influence far, far from where they originated.

Maxwell argued that light too is an electromagnetic wave. But his ideas met with some resistance. While physicists could imagine electromagnetic waves moving through a medium, such as a wire, they had trouble envisaging light as an electromagnetic wave moving through the vacuum of space, as it would have to.

But even before questions about the nature of light could be answered, Maxwell's hypothesis about electromagnetism had to be proved. In 1879, the Prussian Academy of Sciences (in Berlin) put out a call for what came to be called the Berlin Prize problem. The prize was for experimentally verifying Maxwell's ideas. Entries were due by March 1, 1882, with the winner to be awarded 100 ducats (a ducat was either a gold or a silver coin used in Europe during the Middle Ages, and even into the nineteenth and early twentieth centuries). One of the scientists thought most likely to win the prize was the prodigiously talented German physicist Heinrich Hertz. That year, Hertz considered the problem but gave up on it, for he could see no clear experimental way forward. “But in spite of having abandoned the solution at that time, I still felt ambitious to discover it by some other method,” he later wrote.

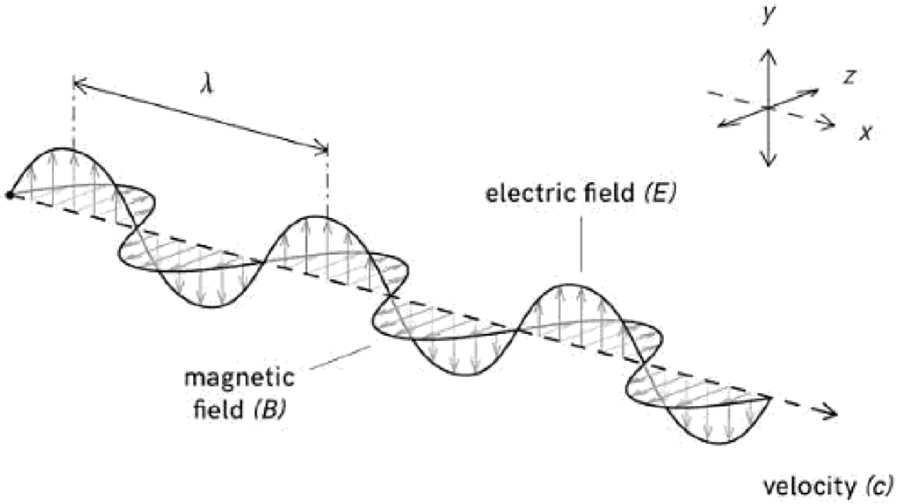
No one won the prize in 1882.

Hertz, however, in just a few years solved the puzzle. He designed an experiment that proved Maxwell correct. The experiment involved building a transmitter of electromagnetic waves, and a receiver—and showing that these invisible waves did indeed exist and could propagate through air. Hertz had inadvertently discovered radio waves.

When asked about the usefulness of such waves, Hertz reportedly said, “It is of no use whatsoever. This is just an experiment that proves Maestro Maxwell was right. We just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.”

Hertz’s experiments validated Maxwell’s theory of electromagnetism. Eventually, it would become clear that light too is an electromagnetic wave. It consists of an electric field and a magnetic field, which each vibrate in mutually perpendicular planes. And light itself travels in a direction that is perpendicular to both the constituent electric and magnetic fields. The frequency of vibration, or the frequency of the electromagnetic wave (ν), turns out to be equal to the velocity of light (c) divided by its wavelength (λ).

But while doing this experiment, Hertz stumbled upon another curious phenomenon that would, within a decade, challenge the light-is-a-wave argument. The phenomenon is now called the photoelectric effect. When light falls on certain metals, it can eject electrons. Most important, for a given metal, the electrons are ejected only when the light is above a threshold frequency unique to that metal. Below that frequency, regardless of how much light falls on the metal, no electrons are ejected. Above the threshold frequency, two things happen. One is that the number of electrons ejected increases as the intensity of the incident light increases. The other is that increasing the frequency of the light increases the energy of the ejected electrons.



$$\text{frequency } (\nu) = \frac{\text{velocity } (c)}{\text{wavelength } (\lambda)}$$

Hertz, however, had seen only glimmers of this phenomenon. His receiver, which was intercepting invisible radio waves, worked better when it was illuminated by light, compared to when it was in darkness inside an enclosure. The radio waves had nothing to do with the light, yet something about the light was influencing the receiver. In a letter he wrote to his father in July 1887, Hertz was characteristically modest about his finding: “To be sure, it is a discovery, because it deals with a completely new and very puzzling phenomenon. I am of course less capable of judging whether it is a beautiful discovery, but of course it does please me to hear others call it that; it seems to be that only the future can tell whether it is important or unimportant.”

It’s not surprising that what Hertz had observed could not be explained at the time. Physicists were yet to discover electrons, let alone understand the photoelectric effect in all its intricacies. Even as late as the early 1890s, our conception of reality was that atoms were the smallest constituents of the material world, but the structure of the atom was still unknown. The discovery of the electron and other important milestones lay on the path from Hertz to Einstein to quantum mechanics.

Hertz, sadly, didn't live to see any of them. He died on January 1, 1894. An obituary in the journal *Nature* recounted his last days: "A chronic, and painful, disease of the nose spread . . . and gradually led to blood poisoning. He was conscious to the last, and must have been aware that recovery was hopeless; but he bore his sufferings with the greatest patience and fortitude." Hertz was only thirtyseven. His mentor, Hermann von Helmholtz (who would himself die later that year) wrote in the preface to Hertz's monograph *The Principles of Mechanics:* "Heinrich Hertz seemed to be predestined to open up to mankind many of the secrets that nature had hitherto concealed from us; but all these hopes were frustrated by the malignant disease which . . . robbed us of this precious life and of the achievements which it promised."

The secrets of nature that Hertz would surely have helped discover came thick and fast. The first one was the discovery of the electron, thanks to something called a cathode ray tube. The tube —essentially a sealed glass cylinder with electrodes on either end, and from which much of the air had been removed—was a scientific curiosity in the mid-nineteenth century. When a high voltage was applied across the electrodes, the tube would light up, and scientists reveled in showing these off to lay audiences. Soon, physicists discovered that pumping out more air, but not all of it, revealed something dramatic: rays seemed to emerge from the negative electrode (the cathode) and streak across to the positive electrode (the anode).

Three years after Hertz's death, the English physicist J. J. Thomson, using a series of elegant experiments, showed unequivocally that these rays were constituents of matter that were smaller than atoms, and their trajectories could be bent by an electric field in ways that proved the rays had negative charge. Thomson had discovered the electron. He, however, called them corpuscles. Thomson speculated these were literally bits of atoms. Not everyone agreed with his pronouncements. "At first there were very few who believed in the existence of these bodies smaller than atoms," he would later say. "I was even told long afterwards by a distinguished physicist who had been present at my lecture at the Royal Institution that he thought I had been ‘pulling their legs.’”

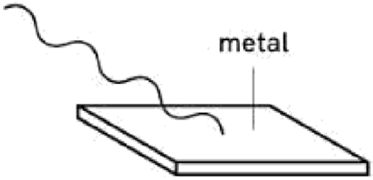
Such doubts aside, Thomson changed our conception of the atom forever.

Meanwhile, after Hertz had made his initial discovery of the photoelectric effect, his assistant, Philipp Lenard, took up the cause. He was a fantastic experimentalist. His experiments clearly showed that ultraviolet light falling on metals produced the same kind of particles as seen in the cathode ray tubes: electrons. Crucially, the velocity of these electrons (and hence their energy) did not depend on the intensity of the incident light. Lenard, however, was a dodgy theorist and made a hash of trying to explain why.

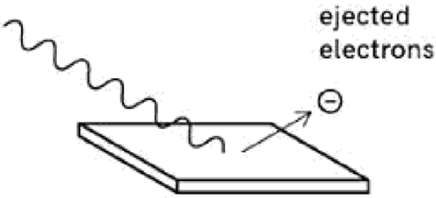
Enter Einstein. In 1905, Einstein wrote a paper on the photoelectric effect. In this paper, he referred to work by the German physicist Max Planck, who five years earlier had drawn first blood in the tussle between classical Newtonian physics and the soon-to-be-formulated quantum mechanics. Planck was trying to explain the behavior of certain types of objects called black bodies, which are idealized objects in thermal equilibrium that absorb all the infalling radiation and radiate it back out. If the electromagnetic energy being emitted is infinitely divisible into smaller and smaller amounts, as it is in classical physics, thus making for a seamless continuum, then the predictions made by theory were at odds with experimental data. Something was not quite right with classical notions of energy.

To solve the puzzle, Planck argued that the spectrum of the black body electromagnetic radiation could be explained only if one thought of energy as coming in quanta, which are the smallest units of energy. Each unit is a quantum, and this quantum is a floor: for a given frequency of electromagnetic radiation, you cannot divide the energy into packets any smaller (the way you cannot divide a dollar into anything smaller than a cent). Using this assumption, Planck beautifully explained the observations. The idea of the quantum was born.

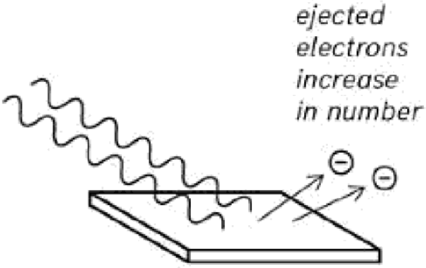
While Einstein did not fully embrace Planck’s ideas in his 1905 paper to explain the photoelectric effect, he would eventually do so. Einstein argued that since light is electromagnetic radiation, it too comes in quanta: the higher the frequency of the light, the higher the energy of each quantum. This relation is linear—doubling the frequency doubles the energy of the quantum. Einstein's claim about light coming in quanta was crucial to understanding the photoelectric effect, in which light falling on a metal can sometimes dislodge an electron from an atom of the metal. For any given metal, said Einstein, an electron can be freed from the metal's surface only if the incident quantum of light has a certain minimum amount of energy: anything less, and the electrons stay put. This explains why electrons never leave the metal surface if the incident light is below a threshold frequency: the quantum of energy is too low. And it does not matter if two quanta put together have the necessary amount of energy. The interaction between light and an atom of metal happens one quantum at a time. So, just pumping more and more quanta below the threshold frequency has no effect.



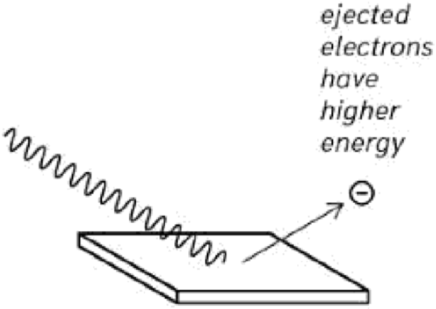
Incident light below threshold frequency



Incident light above threshold frequency



At greater intensity



At higher frequency

With this theory, Einstein also predicted that the ejected electrons will get more energetic (or have greater velocities) as the frequency of the incident light increases. There is more energy in each quantum of light, and this imparts a stronger kick to the electron, causing it to fly out of the metal at a greater speed—a prediction that would soon get experimentally verified.

Einstein's profound claim here was that light is made of small, indivisible particles, where the energy of each particle or quantum depends on the frequency or color of the light. The odd thing, of course, is that terms like *frequency* and *wavelength* refer to the wave nature of light, and yet these were getting tied to the idea of light as particles. A disturbing duality was beginning to raise its head. Things were getting confusing.

Both Lenard and Einstein got Nobel Prizes for their work, Lenard in 1905 for his "work on cathode rays," and Einstein in 1921, for explaining the photoelectric effect using Planck's quantum hypothesis. Lenard, however, became deeply resentful of the accolades given to Einstein for theorizing about what Lenard regarded as his result. Lenard was an anti-Semite. In 1924, he became a member of Hitler's National Socialist party. In front of his office at the Physics Institute in Heidelberg, there appeared a sign that read: "Entrance is forbidden to Jews and members of the so-called German Physical Society." Lenard viciously attacked Einstein and his theories of relativity, with undisguised racism and anti-Semitism. "Einstein was the embodiment of all that Lenard detested. Where Lenard was a militaristic nationalist, Einstein was a pacifistic internationalist . . . Lenard decided that relativity was a 'Jewish fraud' and that anything important in the theory had been discovered already by 'Aryans,'" Philip Ball wrote in *Scientific American.*

In the midst of terrible social unrest and unhinged ideologies across Europe, the quantum revolution was set in motion.

As things stood in 1905, electrons were constituents of atoms (but it was still unclear whether that was the full story about the makeup of atoms). Plus, there were electromagnetic fields, which were described by Maxwell's equations. These came in quanta. It was clear that light too is an electromagnetic wave, which came in quanta and these quanta could be thought of as particles. Microscopic reality did not make a whole lot of sense.

J. J. Thomson, meanwhile, had a question he wanted answered. What would happen when a few quanta of light went through a single slit (rather than two slits)? In 1909, a young scientist named Geoffrey Ingram Taylor started working with Thomson at his laboratory in Cambridge. Taylor decided to design an experiment to try and answer Thomson's question. The answer resonates within quantum mechanics even today, and is particularly relevant for the story of the double-slit experiment.

Picture a source of light that shines on an opaque sheet with a single slit. On the other side of the opaque sheet is a screen. Again, our naive expectation is that we'll see a single strip of light on the screen. Instead, what appear are fringes (albeit a different pattern than seen with the double slit. In the case of a single slit, the fringes can be explained by thinking of each point in the opening or aperture of the slit as a source of a new wave. These waves then interfere with each other, leading to what's called a diffraction pattern). It's another proof that light behaves like a wave. When there's lots of light, the results are easy to explain: light is an electromagnetic wave, and so we should see fringes.

But given that light also comes in quanta, or particles, Thomson wanted to understand the single-slit phenomenon when the intensity of light falling on the single slit is turned way down, so that only a few quanta of light go through the slit at any one time. Now, if the screen on the far side is a photographic plate that records each quantum of light, then over time, would one see interference fringes? Thomson argued that there should be blurry fringes, because in order to get sharp fringes, numerous quanta should arrive simultaneously at the screen and interfere. Reducing the quanta reaching the screen at the same time to a trickle should reduce the amount of interference and hence the sharpness of the fringes, Thomson hypothesized.

Taylor was in his twenties and starting out on his career as an experimental physicist. He chose this experiment as the subject of his first scientific paper, but oddly, he recalled years later, "I chose that project for reasons which, I fear, had nothing to do with its scientific merits." Consequently, he performed the experiment in the children's playroom of his parents' home. To create a single slit, he stuck metal foil onto a piece of glass and, using a razor blade, etched a slit in the metal foil. For a source of light he used a gas flame. Between the flame and the slit, he placed many layers of darkened glass. Taylor calculated that the light falling on the single slit was so faint that it was equivalent to a candle burning a mile away. On the other side of the slit, Taylor placed a needle, whose shadow he captured on a photographic plate. The light—ostensibly just a few quanta at a time—passed through the slit and landed on the photographic plate. What would the plate record after weeks of exposure to the faint light?

Taylor's mind, meanwhile, was elsewhere. He was becoming an accomplished sailor. He set up his experiment so that he could get enough of an exposure on the photographic plate after six weeks. "I had, I think rather skillfully, arranged that this stage would be reached about the time when I hoped to start a month's cruise in a little sailing yacht I had recently purchased," he said. During the longest stretch of the experiment, in which the photographic plate was exposed for three months, Taylor reportedly went away sailing.

After that three-month-long exposure, Taylor saw interference fringes—as sharp as if the photographic plate had been exposed to more intense light for a very short time. Thomson was proved wrong. Taylor never followed up on this negative result. If he had, he might have played an important role in the development of quantum mechanics—for his results were hinting at the odd behavior of photons. Instead of pursuing this any further, Taylor changed directions and went on to make seminal contributions to other fields of physics, particularly fluid mechanics.

Thomson, however, wasn't done being a mentor. In the autumn of 1911, a young Danish scientist named Niels Bohr came to work with Thomson. Soon thereafter, Bohr moved to Manchester to study with New Zealand–born British physicist Ernest Rutherford, who was probing the structure of the atom. Rutherford's work had established that the atom, besides having electrons, also has a positively charged nucleus. Calculations showed that much of the mass of the atom is in the nucleus. What emerged was a new picture of an atom: negatively charged electrons orbiting a positively charged nucleus, the way planets orbit the sun.

Almost immediately, physicists realized that this model had serious shortcomings. Newton's laws mandated that orbiting electrons had to be accelerating, if they were to remain in their orbits without falling into the nucleus. And Maxwell's equations showed that accelerating electrons should radiate electromagnetic energy, thus lose energy and eventually spiral into the nucleus, making all atoms unstable. Of course, that's not what happens in nature. The model was wrong.

An interim solution came courtesy of the young Bohr. In 1913, Bohr proposed that the energy levels of electrons orbiting a nucleus did not change in a continuous manner, and also that there was a limit to the lowest energy level of an electron in an atom. Bohr was arguing that the orbits of the electrons and hence their energy levels were quantized. For any given nucleus, there's an orbit with the lowest possible energy. This orbit would be stable, said Bohr. If an electron were in this lowest-energy orbit, it could not fall into the nucleus, because to do so, it'd have to occupy even smaller orbits with lower and lower energies. But Bohr's model prohibited orbits with energies smaller than the smallest quantum of orbital energy. There was nowhere lower for the electron to fall. And apart from this stable, lowest-energy orbit, an atom has other orbits, which are also quantized: an electron cannot go from one orbit to another in a continuous fashion. It has to jump.

To get a sense for how weird it must have been for physicists in the early twentieth century to understand Bohr's ad hoc claims, imagine you are driving your car and want to go from 10 to 60 miles per hour. In an analogy to the way electrons behave in orbits, the car jumps from 10 mph to 60 mph in chunks of 10 mph, without going through any of the intermediate speeds. Moreover, no matter how hard you brake, you cannot slow the car down to below 10 mph, for that's the smallest quantum of speed for your car.

Bohr also argued that if an electron moves from a high-energy to a low-energy orbit, it does so by emitting radiation that carries away the difference in energy; and to jump to an orbit with higher energy, an electron has to absorb radiation with the requisite energy.

To prevent electrons from losing energy while orbiting the nucleus, which they would have to according to Maxwell's theory, Bohr argued that the electrons existed in special "stationary" states, in which they did not radiate energy. The upshot of this somewhat arbitrary postulate was that another property of electrons, their angular momentum, was also quantized: it could have certain values and not others.

It was all terribly confounding. Nonetheless, there were connections emerging between the work of Planck, Einstein, and Bohr. Planck had shown that the energy of electromagnetic radiation was quantized, where the smallest quantum of energy (E) was equal to a number called Planck's constant (h) multiplied by the frequency of the radiation (v), producing his famous equation $E=hv$. Einstein showed that light came in quanta, and the energy of each quantum or photon was also given by the same equation, $E=hv$ (where v refers to the frequency of the light).

While Bohr had shown that the energy levels in atoms were quantized, it'd take him a decade or so more to accept that when electrons jumped energy levels, the radiation going in or coming out of the atom was in the form of quanta of light (Bohr initially insisted that the radiation was classical, wavelike).

But when Bohr did accept Einstein's idea of light quanta, he saw that the absorbed or emitted energy of the photons was given by, again, $E=hv$. (Bohr wasn't the only big name resisting Einstein's ideas. The notion of light being quantized was hard to stomach for physicists, given the success of Maxwell's equations of electromagnetism in describing the wave nature of light. For instance, Planck, when he was enthusiastically recommending Einstein for a seat in the Prussian Academy of Sciences in 1913, slipped in this caveat about Einstein: "That he might sometimes have overshot the target in his speculations, as for example in his light quantum hypothesis, should not be counted against him too much.")

Still, the evidence for nature's predilection for sometimes acting like waves and sometimes like particles continued to grow. In 1924, Louis de Broglie, in his PhD thesis, extended this relationship to particles of matter too, and provided a more intuitive way to envision why the orbits of electrons are quantized. Matter, said de Broglie, also exhibited the same wave-particle duality that Einstein had shown for light. So an electron could be thought of as both a wave and a particle. And atoms too. Nature, it seems, did not discriminate: everything had wavelike behavior and particle-like behavior.

The idea helped make some sense of Bohr's model of the atom. Now, instead of thinking of an electron as a particle orbiting the nucleus, de Broglie's ideas let physicists think of the electron as a wave that circles the nucleus, the argument being that the only allowed orbits are those that let the electron complete one full wavelength, or two, three, four, and so on. Fractional wavelengths are not allowed.

It was clear by then that physics was undergoing a profound transformation. Physicists were beginning to explain previously inexplicable phenomena, using these ideas of quantized electromagnetic radiation, quantized electron orbits, and the like, at least for the simplest atom, that of hydrogen, which has one electron orbiting the nucleus. More complex atoms were not so easily tamed, even with these new concepts. Still, what was being explored was the very structure of reality—how atoms behave and how the electrons inside atoms interact with the outside world via radiation, or light. But the successes notwithstanding, the puzzles were also mounting.

While nature's discontinuity and discreteness at the smallest scales was becoming ever more obvious, there was the puzzling issue of its concomitant wave nature, emblematic of classical continuity. And, probably most disturbingly, there was the question of indeterminism. It was clear that there are natural phenomena that do not follow the clockwork determinacy of Newton's classical world. Take, for example, radioactivity: nothing about the current state of a radioactive atom lets you predict exactly when it'll emit a ray of radioactivity. The process is unpredictable, stochastic. This went against the tenets of the science of the time, according to which full knowledge of a system should let you predict with precision some future event involving that system. The microscopic world seemed to be operating with a different set of rules.

But it wasn't obvious what these rules were. What physics lacked was an overarching framework that brought these disparate elements together. All that changed during the mid to late 1920s, when in a few feverish years, brilliant minds forged not one but two frameworks for theorizing about the world at small scales. This effort would culminate in one of the most celebrated scientific conferences in history—the Fifth Solvay International Conference on Electrons and Photons held in October 1927 in Brussels, Belgium. The moment, captured in a now-iconic photograph taken by Belgian photographer Benjamin Couprie, shows all twenty-nine attendees, some standing in the back row still in their twenties and yet to become famous, some already so and seated in the front row, including Einstein, Planck, and Marie Curie, and almost everyone else in between who mattered to the emerging field of quantum physics. If they weren't already Nobel Prize winners, many would go on to win—turning seventeen of the twenty-nine into Nobel laureates.

"The lakes" of Copenhagen are five reservoirs that stretch crescentshaped not far from the city center. Walk along the northern end of these lakes, go past a stretch of shore lined with horse chestnut trees, down a couple of blocks along an alley named Irmingersgade, and you come up, quite suddenly, on an unassuming building: the Niels Bohr Institute. When it was founded in 1921 by Bohr, it was called the Institute of Theoretical Physics. Bohr had moved from Manchester to the University of Copenhagen, where he became a professor in 1916 at just thirty-one years of age. He then lobbied hard and got the funds to build an institute for theoretical physics. And for a few decades, the institute became a cauldron where great minds stewed over the evolving field of quantum physics, under Bohr's deeply engaged gaze.

One of these great minds was a young German physicist named Werner Heisenberg. Bohr first met Heisenberg at Göttingen, Germany, in June 1922. Bohr was there to talk about the current understanding of the model of the atom and the various outstanding problems yet to be solved. During the talk, Heisenberg, still a twenty-year-old student in his fourth semester, questioned Bohr with such clarity that a suitably impressed Bohr took Heisenberg for a walk afterward to discuss atomic theory. He also invited Heisenberg to Copenhagen, and it was there in 1924 that Heisenberg realized, after discussions with Bohr and others, that "perhaps it would be possible one day, simply by clever guessing, to achieve the passage to a complete mathematical scheme of quantum mechanics." The word *mechanics* refers to physics that can explain how something changes with time under the influence of forces.

Heisenberg's insight was prophetic. In the spring of 1925, suffering from severe hay fever, he decamped to Helgoland in the North Sea, a rocky island devoid of pollen. There, between long walks and contemplating Goethe's *West-östlicher Divan*, he developed the early mathematics that would become the basis for modern quantum theory. Heisenberg recalled later, "It was almost three o'clock in the morning before the final result of my computations lay before me . . . I could no longer doubt the mathematical consistency and coherence of the kind of quantum mechanics to which my calculations pointed. At first, I was deeply alarmed. I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structures nature had so generously spread out before me. I was far too excited to sleep, and so, as a new day dawned, I made for the southern tip of the island, where I had been longing to climb a rock jutting out into the sea. I now did so without too much trouble, and waited for the sun to rise."

Heisenberg wrote up his work, showed it first to Wolfgang Pauli (another of the brilliant young minds) and then to Max Born (an equally brilliant but a more fatherly figure in his forties, with whom Heisenberg was doing his postdoctoral work). Born immediately realized the import of Heisenberg's paper. "I thought the whole day and could hardly sleep at night . . . In the morning I suddenly saw the light," he would say.

What Born realized was that the symbols Heisenberg was manipulating in his equations were mathematical objects called matrices, and there was an entire field of mathematics devoted to them, called matrix algebra. For example, Heisenberg had found that there was something strange about his symbols: when entity A was multiplied by entity B, it was not the same as B multiplied by A; the order of multiplication mattered. Real numbers don't behave this way. But matrices do. A matrix is an array of elements. The array can be a single row, a single column, or a combination of rows and columns. Heisenberg had brilliantly intuited a way of representing the quantum world and asking questions about it using such symbols, while being unaware of matrix algebra.

In a few frenetic months, Born, along with Heisenberg and Pascual Jordan, developed what's now known as the matrix mechanics formulation of quantum physics. In England, Paul Dirac saw the light too when he encountered Heisenberg's work, and he too, in a series of papers, independently added tremendous insight and mathematics to the formulation and developed the "Dirac notation" that's still in use today.

Most important, it was clear that the formalism worked. For example, the position of, say, an electron, is represented by a matrix. The position in this case is called an observable. The matrix then dictates all the possible positions in which the electron can be found, or observed. The formalism implicitly allows for the electron to be only in certain positions and not in others. And there is no sense of a continuous change from one position to another. Discreteness, or jumps from one state to another, is baked into matrix mechanics.

In due course, physicists were able to use the formalism to calculate, for example, the energy levels of electrons in atoms, explain the radiation emitted by glowing bits of sodium or other metals, understand how such spectral emissions could be split into slightly different frequencies under the influence of a magnetic field, and better understand the hydrogen atom itself.

But it wasn't obvious why the formalism worked. What did these matrices map to, physically speaking? The elements of these matrices could be complex numbers (a complex number has a real part and an imaginary part; the imaginary part is a real number multiplied by the square root of -1 and is imaginary because $\sqrt{-1}$ doesn't exist yet turns out to be incredibly useful in certain kinds of mathematics). How could the physical world be represented by things that could only be imagined? Were we at the very limit of human understanding? Was a clear understanding possible?

Matrix mechanics does not allow physicists to think of electrons as having clear, fixed orbits, even if they are quantized. One can describe an electron's quantum state using a set of numbers, carry out a whole lot of matrix manipulations to predict things like spectral emissions, but what you lose is the ability to visualize the electron's orbit in the way that one can visualize, say, Earth's orbit around the sun.

Plus, the formalism deals in probabilities. If a particle is in state A and you measure to see if it's state A, then, of course, the math says you'll find the particle in state A with 100 percent certainty. The same goes for, say, state B. But matrix mechanics says that a particle can be in some intermediate state, where the state is x parts A and y parts B. Now, if you try and predict whether you'll find the particle in state A or state B, 100 percent certainty about reality is no longer possible.

Matrix mechanics lets you calculate only the probabilities of outcomes of measurements. So, for an electron whose state is x parts A and y parts B, say you want to see if the particle is in state A. The math says that the probability of finding the particle in state A is x^2. Similarly, if you check to see if the particle is in state B, the probability you'll find it in state B is y^2. (The terminology gets tweaked a little bit when you allow x and y to be complex numbers, but for now, it's easy to see what rules x and y have to follow: the probabilities have to add up to one, so $x^2 + y^2$ should equal 1.)

The fact that we are now dealing in probabilities is not, presumably, because we do not know enough about the particle. Matrix mechanics says you have all the information you can possibly have. Yet, if you take a million identically prepared particles in the same state (the same combination of states A and B) and perform a million identical measurements, then, on average, x^2 number of times you will find the particle in state A, y^2 of the time you'll find it in state B. But you can never predict the answer you'll get for any single particle. You can only talk statistically. Nature, it seems, is not deterministic in the quantum realm.

Recall that something similar happens with the double slit. We cannot predict where exactly a single photon will land on the screen—we can only assign probabilities for where it might go.

Soon after these phenomenal developments, an Austrian physicist named Erwin Schrödinger, whose status as a founding member of quantum physics was yet to be established, expressed his dismay at, even distaste for, Heisenberg's matrix mechanics. He said he was "discouraged, if not repelled" by what he saw as "very difficult methods of transcendental algebra, defying any visualization."

The battle lines were being drawn. Wave versus particle, continuous versus discrete, old versus new. Schrödinger's distaste led him to develop a formidable old-school alternative to the upstart, matrix mechanics—one that seemed to restore faith in the classical way of thinking about nature.

When Louis de Broglie wrote his 1924 thesis on the wave-particle duality of matter, Schrödinger was already a professor of theoretical physics at the University of Zurich, and compared to the young geniuses elsewhere in Europe, he was practically an old man, approaching forty. But for years Schrödinger had been delving into the same questions that had been tormenting everyone. Schrödinger learned of de Broglie's work when he read a reference to it in a paper by Einstein. Thinking of matter as waves made sense to Schrödinger's classically intuitive mind, and he acknowledged as much in a letter to Einstein, dated November 3, 1925: "A few days ago I read with the greatest interest the ingenious thesis of Louis de Broglie, which I finally got hold of." Schrödinger wanted to describe the motion of electrons around the nucleus by thinking of them as waves. Instead of Heisenberg's matrix mechanics, Schrödinger wanted wave mechanics for electrons.

If Heisenberg's solo sojourn at Helgoland has become quantum physics lore, so has Schrödinger's own burst of creativity in isolation—well, almost in isolation. A *New York Times* book review captures this period in Schrödinger's life: "A few days before Christmas, 1925, Schrödinger . . . took off for a two-and-a-half-week vacation at a villa in the Swiss Alpine town of Arosa. Leaving his wife in Zurich, he took along de Broglie's thesis, an old Viennese girlfriend (whose identity remains a mystery) and two pearls. Placing a pearl in each ear to screen out any distracting noise, and the woman in bed for inspiration, Schrödinger set to work on wave mechanics. When he and the mystery lady emerged from the rigors of their holiday on Jan 9, 1926, the great discovery was firmly in hand."

Within weeks, Schrödinger published his first paper in the *Annalen der Physik*. Three more papers followed in quick succession, and Schrödinger turned the world of Heisenberg and Born upside down. Suddenly, physicists had an intuitive way of understanding what was ostensibly happening to an electron in a hydrogen atom. Schrödinger had come up with his now eponymous wave equation, which treated the electron as a wave, and showed how this wave would change over time. It was wave mechanics. It was almost classical physics, except there were curious and consequential differences.

In classical physics, solving a wave equation for, say, a sound wave can give you the pressure of the sound wave at a certain point in space and time. Solving Schrödinger's wave equation gives you what's called a wavefunction. This wavefunction, denoted by the Greek letter ψ (psi, pronounced "sigh"), is something quite strange. It represents the quantum state of the particle, but the quantum state is not a single number or quantity that reveals, for example, that the electron is at this position at this time and at that position at another time. Rather, ψ is itself an undulating wave that has, at any given moment in time, different values at different positions. Even more weirdly, these values are not real numbers; rather, they can be complex numbers with imaginary parts. So the wavefunction at any instant in time is not localized in a region of space; rather, it is spread out, it's everywhere, and it has imaginary components. The Schrödinger equation, then, allows you to calculate how the state of the quantum system, ψ, changes with time.

Schrödinger thought the wavefunction provided a way to visualize what was actually happening to electrons or other inhabitants of the quantum world. But this view was challenged within months of Schrödinger's papers being published, when Max Born realized that Schrödinger was wrong about the meaning of the wavefunction.

In a couple of seminal papers published in the summer of 1926, Born showed that when electrons collide and scatter, the resulting wavefunction that represents the state of the electrons only encodes the probability of finding the electrons in one state or another. It took Born a couple of tries to get it right, but he showed that if ψ is the wavefunction of an electron, and if it can be written, for example, in terms of two different possible states of the electron, ψA and ψB, such that $\psi = \text{x}.\psi\text{A} + y.\psi\text{B}$, then all you can do is calculate the probability that you'll find the electron in state A or state B when you do a measurement. (The probability of finding the electron in state A is given by the square of the amplitude of x, also called the square of the modulus of x, denoted as $|x|^2$, and the probability of finding it in state B is given by $|y|^2$. If x is, say, a real number, the modulus $|x|$ is simply its absolute value: if it's positive to start with, it remains positive; if it's negative, then we multiply it by -1; squaring it gives us a positive number. Of course, x and y can be complex numbers, and calculating the modulus of a complex number is a bit more complicated, but in essence, when you take the modulus-squared of a complex number, you again get a number that is positive and real, without any imaginary parts.)

Born had, it seemed at first blush, cast doubt on causality, the underpinning of deterministic classical physics, which says any given effect has a cause. Given an initial state of an electron, standard quantum mechanics cannot definitively say what the electron's next state will be. One can only calculate the probability of an electron transitioning to some new state, using what came to be called the Born rule. An element of randomness, or stochasticity, became an integral part of the laws of nature. As Born put it, "The motion of particles follows probability laws but the probability itself propagates according to the law of causality."

And there it was—one interpretation of the wavefunction. It's a probability wave. Schrödinger's equation lets you calculate how this wave changes with time deterministically, but as it evolves and takes on different shapes, what's changing are the probabilities of finding the quantum system in various states.

If this sounds like the probabilities of matrix mechanics, you are not mistaken. Schrödinger himself, in another stroke of insight, showed that wave mechanics and matrix mechanics are mathematically equivalent (in hindsight, it was a mathematician called John von Neumann who would really prove the equivalence a few years later). Rather than see this as a validation of matrix mechanics, Schrödinger claimed victory for wave mechanics, considering his approach to be correct and arguing that anything that was calculated using matrix mechanics could be calculated using wave mechanics. The advantage of wave mechanics, in Schrödinger's opinion, was the idea that nature even at the smallest scales was continuous, not discrete. There were no quantum jumps.

Heisenberg, meanwhile, wasn't enamored of Schrödinger's ideas. He wrote to Pauli, complaining that he found them "abominable," calling it "*Mist*" (which is German for rubbish, manure, dung, or droppings). Pauli himself alluded to *Züricher Lokalaberglauben* (local Zurich superstitions, an allusion to the city where Schrödinger worked). Schrödinger, unsurprisingly, wasn't pleased by Pauli's assertions. Pauli, in turn, tried to appease Schrödinger by saying, "Don't take it as a personal unfriendliness to you but look on the expression as my objective conviction that quantum phenomena naturally display aspects that cannot be expressed by the concepts of continuum physics. But don't think that this conviction makes life easy for me. I have already tormented myself because of it and will have to do so even more."

The torment these titans felt over the nature of reality continued when Schrödinger visited Copenhagen and met Bohr for the very first time.

Decades after Schrödinger's visit to Copenhagen in September 1926, Heisenberg would recount the intensity of their meetings: "The discussion between Bohr and Schrödinger began at the railway station in Copenhagen and was carried on every day from early morning till late at night. Schrödinger lived at Bohr's house so that even external circumstances allowed scarcely any interruptions of the talks. And although Bohr as a rule was especially kind and considerate in relations with people, he appeared to me now like a relentless fanatic, who was not prepared to concede a single point to his interlocutor or to allow him the slightest lack of precision. It will scarcely be possible to reproduce how passionately the discussion was carried on from both sides."

So passionately that even after Schrödinger fell sick and was bedridden with a fever and cold, the host did not relent. Bohr turned up at his bedside to debate quantum physics, even as Bohr's wife, Margrethe, took care of Schrödinger.

The debate between Bohr and Schrödinger was a foretaste of future debates that Bohr would have with Einstein about how to think about the smallest constituents of reality (at the time, electrons and photons). It was a clash of two ways of thinking. As Walter Moore writes in his book *Schrödinger: Life and Thought*, "Schrödinger was a 'visualizer' and Bohr was a 'nonvisualizer,' one thought in terms of images and the other in terms of abstractions."

Schrödinger left Copenhagen, but Heisenberg was still there to serve as Bohr's debating partner. Heisenberg was now living in an attic apartment at the institute, and it was there that Bohr would turn up late at night to continue their arguments. And though the two were mostly on the same side of the debate, they still had differences: Bohr wanted to make wave-particle dualism—the idea that nature has two faces and only shows one or the other at any one time—a key component of any interpretation of reality; Heisenberg put his “trust in the newly developed mathematical formalism,” to see what meanings it suggested, rather than presupposing any particular view of reality.

They fretted about making sense of experiments, including the double slit. As Heisenberg would say, “Like a chemist who tries to concentrate his poison more and more from some kind of solution, we tried to concentrate the poison of the paradox, and the final concentration was such experiments like the electron with the two holes . . . They were just a kind of quintessence of what was the trouble.”

By the end of February 1927, their discussions at an impasse, Bohr went off to ski in Norway. Heisenberg too took time for himself. He wrote of one extraordinary night when something clarified: “I went for a walk in the Fælledpark, which lies behind the institute, to breathe the fresh air and calm down before going to bed. On this walk under the stars, the obvious idea occurred to me that one should postulate that nature allowed only [those] experimental situations to occur which could be described within the framework of the formalism of quantum mechanics. This would apparently imply, as one could see from the mathematical formalism, that one could not simultaneously know the position and velocity of a particle.”

Heisenberg had discovered the uncertainty principle. The formalism of quantum mechanics has pairs of observable quantities, such as the position and momentum of a particle, where trying to determine one with increasing precision means that you increase the imprecision of the values you obtain for the other. So, if you know exactly where a particle is, you have very little idea of its momentum, and vice versa. This relation extends to other pairs of quantities, such as energy and time.

(When I visited the Niels Bohr Institute, I went up to the attic to see Heisenberg’s living quarters. His apartment was being used by builders to store air-conditioning equipment. A cartoon captioned “At home with the Heisenbergs” was stuck on the bathroom door outside the apartment, with Mrs. Heisenberg saying, “I can’t find my car keys,” and Mr. Heisenberg replying, "You probably know too much about their momentum.")

Bohr, meanwhile, became ever more convinced that what he called the principle of complementarity was at the heart of quantum mechanics: that wave nature and particle nature are complementary aspects of reality, and that it's our choice of experiment that reveals one or the other, but never both at the same time. He thought that the uncertainty principle was one outcome of the broader principle of complementarity.

Elsewhere, Einstein was growing deeply concerned about such interpretations of the quantum formalism, and building himself up toward a profound intellectual debate with Bohr, a debate that would shape the future of quantum mechanics. Einstein had a predilection for conjuring up thought experiments to make a point —and one of these involved the double-slit experiment. He brought it up at the Fifth Solvay Conference.

History has often portrayed Einstein and Bohr as giants in battle, slashing at each other with their respective intellectual might. But often what gets lost in the retelling is the enormous respect and affection that the two had for each other. Einstein and Bohr met for the first time in Berlin in April 1920. Impressed by Bohr, Einstein wrote to him in May, from America, beginning his letter with these words: "Dear Mr. Bohr: The magnificent gift from the neutral world, where milk and honey still flow, gives me a welcome occasion to write to you. Not often in life has a person, by his mere presence, given me such joy as you. I understand why [Paul] Ehrenfest is so fond of you." Bohr wrote back in June, saying, "To meet you, and talk with you, was one of the greatest experiences I have ever had."

This mutual admiration underpinned their relationship, despite their strong disagreements over quantum mechanics.

Their friendly salvos were fired in earnest at the Fifth Solvay Conference in Brussels. This was a grand battle of ideas, the likes of which occur infrequently enough in science to be etched in cultural memory as moments that changed our understanding of our place in the universe. Sometimes the individuals debating have been separated by the intervening centuries, as was the case with

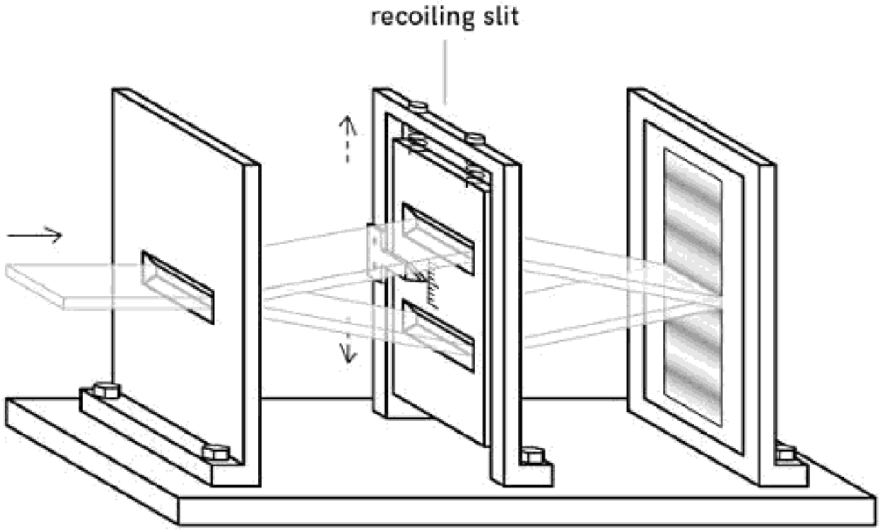
Copernicus, who in the sixteenth century argued against the Greek astronomer and mathematician Ptolemy's ancient theory that Earth is at the center of the solar system. Copernicus put the sun at the center. Sometimes, it's one person's fight against an emerging consensus, as was the case in the 1950s with English astronomer Fred Hoyle's increasingly isolated stand for a steady-state universe, when theory and evidence were both pointing to an expanding cosmos that began in a big bang. And at times, the antagonists debated the nature of scientific progress itself, as happened between philosophers Karl Popper and Thomas Kuhn. Popper, impressed by Einstein's work on relativity, argued that science progresses in increments; scientists come up with hypotheses to explain phenomena, hypotheses that they then try their best to falsify. Kuhn would be influenced by the goings-on at the Fifth Solvay Conference and argued that science mostly moves along in the manner suggested by Popper, with scientists working within an accepted paradigm, until anomalies—things that cannot be explained within the current way of thinking—pile up, bringing science to the brink of crisis, causing an upheaval and a dramatic paradigm shift.

The debates at the Fifth Solvay Conference set the stage for just such a shift. Bohr, Heisenberg, and Pauli were making a case for what eventually came to be called the Copenhagen interpretation of quantum mechanics. According to them, the only aspects of reality that you could know about were those that were allowed by the formalism. For example, you could ask about the probability of finding an electron somewhere, but you couldn't ask what path it took to get there, because there is nothing in the math that captures an electron's path. It'd take another five years for the math to become sophisticated, thanks to John von Neumann, but the new view of reality was taking hold. Taken at its most extreme, the Copenhagen interpretation is anti-realist: it denies any notion of reality that exists independent of observation. More important, the proponents were claiming that the mathematical formalism is complete, and that there is nothing more to say about reality.

This was, of course, a massive shift in our way of thinking. Until then, our theories said something concrete about a natural world that exists regardless of observation. Einstein, a realist, argued that the mathematical formalism of quantum mechanics was incomplete and did not paint a full picture of reality.

The Solvay Conference was being held at the Institute of Physiology in the heart of Brussels. “However, with all the participants staying at the Hotel Metropole, it was in its elegant art deco dining room that the keenest arguments took place . . . The acknowledged master of the thought experiment, Einstein would arrive at breakfast armed with a new proposal that challenged the uncertainty principle and with it the much-lauded consistency of the Copenhagen interpretation. The analysis would begin over coffee and croissants. It continued as Einstein and Bohr headed to the Institute of Physiology, usually with Heisenberg, Pauli and Ehrenfest trailing alongside. As they walked and talked, assumptions were probed and clarified before the start of the morning session . . . During dinner back at the Metropole, Bohr would explain to Einstein why his latest thought experiment had failed to break the limits imposed by the uncertainty principle. Each time Einstein could find no fault with the Copenhagen response, but they knew, said Heisenberg, ‘in his heart he was not convinced.’”

At the center of one of their mind games was the double-slit experiment. Einstein imagined an electron that first passes through a single slit, and then encounters a double slit, and eventually ends up somewhere at the center of the far screen. In Einstein’s original thought experiment, the single slit could move up and down, while the double slit was fixed, but physicists since then have reimagined the setup with the single slit held in place, and the double slit as the one that can move up or down as it’s buffeted by the particles going through the slits. While conceptually identical to Einstein’s imagined apparatus, the newer version is easier to grasp.



Consider an electron that goes through the single slit, then through the double slit, and then lands at the center of the far screen. Using Einstein's analysis, if the electron went through the lower slit, then it'd have had to change directions and move upward to get to the center of the screen. This would impart a downward kick to the slit itself. And if the electron went through the upper slit, it'd impart an upward kick to the slit. So, by measuring the momentum transfer, one should be able to tell which slit the electron went through, said Einstein. His point was that even though one observes the interference pattern, which demonstrates the electron's wave nature, measuring the slit's momentum tells us about the electron's path on its way to the far screen, thus revealing its particle nature. The two aspects of reality are not mutually exclusive, he claimed, and the fact that quantum mechanics did not have the formalism to capture that fact meant that it was somehow incomplete.

Bohr was stumped for a bit, but soon came back with a retort (in addition to coming up with the drawings that involved bolting the apparatus to a base and other practical things). He pointed out that if the slit can move when the electron passes through, and if we can measure the momentum transfer with precision, then we'll have imprecise knowledge about its location (thanks to

Heisenberg's uncertainty principle). Now, if you do the calculations of where the electrons land on the far screen, taking into account the uncertainty about the slit's position, it turns out the interference pattern gets smudged. Trying to find out which slit the electron went through, by allowing the slits to move, destroys its wave nature. We can see the electrons either as particles or as waves, not both at the same time.

This was, of course, a thought experiment. There was no way to implement such an exquisitely engineered experiment in the 1920s, to get information about the particle's path without destroying the particle. It'd take almost a century of effort to carry out a variation of this thought experiment. It turns out that Bohr was right in this regard: it's impossible to dupe nature. (However, physicists and historians reading Bohr's writings would point out later that Bohr's arguments were somewhat inscrutable, so one should be circumspect about unqualified claims that "Bohr was right"—nonetheless, as experimental evidence goes, it went against Einstein on this count.) The experiment also showed that complementarity is a seemingly more powerful principle than maybe even Bohr imagined.

Such victories in hand, Bohr and company started giving concrete shape to the Copenhagen interpretation and its anti-realist view of nature. In the double-slit experiment, the Copenhagen interpretation makes no claim as to the path of the particle through the apparatus and, some would say, even denies that such a path exists.

Einstein and Bohr continued sparring over what quantum mechanics was telling us about reality. Was quantum physics the whole story? Was the mathematical formalism that described the statistical behavior of the subatomic world a complete description of reality? Or was there a hidden reality that the math wasn't capturing? Bohr metaphorically shrugged his massive shoulders and insisted there was no hidden reality.

Bohr, for his part, kept returning to the double-slit experiment to make philosophical points, sometimes infuriating his audience. Hendrik Casimir, a young physicist who had come to work with Bohr, wrote about a conversation with Bohr and Danish philosophers Harald Høffding and Jørgen Jørgensen. They were all at the Carlsberg mansion (the erstwhile residence of the founder of the Carlsberg brewery). Bohr was talking about the double-slit experiment done with electrons. Someone quipped, “But the electron must be somewhere on its road from source to observation screen.” Bohr pointed out that the answer depends on what one means by the phrase *to be*. An exasperated Jørgensen retorted: “One can, damn it, not reduce the whole of philosophy to a screen with two holes.”

But Bohr wasn’t being flippant. What does it mean *to be* something in the quantum realm? Opinions differ dramatically. And the experiment with two holes, despite Jørgensen’s protestations, remains at the center of these historic, differing scientific and philosophical arguments.

This edition first published in the United Kingdom by
Duckworth in 2020

Duckworth, an imprint of Duckworth Books Group Ltd
1 Golden Court, Richmond
TW9 1EU, United Kingdom
www.duckworthbooks.co.uk

For bulk and special sales please contact
info@duckworthbooks.com

First published in the US by Dutton an imprint of
Penguin Random House LLC in 2018

Portions of chapter 6 appeared in New Scientist magazine. Bohmian trajectories in chapter 6 reproduced with permission from Chris Dewdney. The de Broglie-Bohm and the many interacting worlds trajectories in the epilogue reproduced with permission from Howard Wiseman.

Illustrations by Roshan Shakeel

A catalogue record for this book is available from the British Library

Book design by Daniel Lagin

Printed and bound in Great Britain by Clays

9780715653937