

Carlo Rovelli on what we get wrong about the origins of quantum theory

Conventional accounts of the birth of quantum theory often overlook the pivotal role of one of its luminaries – and this has led to a persistent misunderstanding of what it really means, argues physicist Carlo Rovelli



The story of the birth of [quantum mechanics](#) is often told, but not always correctly, in my opinion. Introductory quantum physics classes focus on the famous equation written by Erwin Schrödinger in 1926, which describes [quantum waves](#). I think the emphasis on these waves has generated a confusion that persists today. The birth of quantum theory happened a year earlier, largely in the work of Max Born and his collaborators. And I like to draw attention to this point not just to give Born deserved credit, but also because I think the emphasis on Schrödinger's waves is responsible for today's confusion about what quantum phenomena tell us about reality.

Let me start from the beginning. It is often said that quantum physics arrived as a surprise at a time when physicists thought they had figured out all the basic laws of nature. There never was such a time. At the end of the 19th century, physicists were confused about plenty of basic things.

This article is part of a special series celebrating the 100th anniversary of the birth of quantum theory. [Read more here.](#)

This is why nobody paid much attention when, in October 1900, Max Planck came up with a simple but unjustified equation in trying to make sense of certain obscure experimental measurements of the electromagnetic radiation inside hot cavities. The equation was $E = h\nu$. It connects the

energy (E) and the frequency (ν) of the radiation via a totally new constant (h), now known as Planck's constant. This constant, we now know, sets the scale of quantum phenomena.

It was [Albert Einstein](#), five years later, who saw what this equation could mean: light is made of [particles](#), or "quanta of light", each having energy $E = h\nu$. This didn't square with what was considered empirically established at the time: that light is a wave. A young postdoctoral researcher today raising a suggestion like Einstein's, so contrary to established views, wouldn't be taken seriously by anybody.

Nor, in fact, was Einstein. He became nearly instantly famous for relativity, but his "quanta of light" were considered outlandish. A recommendation letter to the Berlin ministry urging that a new position be opened for him stated that the young Einstein was a genius and should be excused for silly ideas about quanta of light. But his quanta predicted a physical effect that turned out to be real, and earned him his Nobel prize.

Can we solve quantum theory's biggest problem by redefining reality?

With its particles in two places at once, quantum theory strains our common sense notions of how the universe should work. But one group of physicists says we can get reality back if we just redefine its foundations

Einstein's paper on the subject opens with the words: "It seems to me that [numerous] observations... are more readily understood if one assumes that the energy of light is discontinuously distributed in space". Note the wonderful initial, "It seems to me". Ordinary people have certainties. Genius hesitates.

Quanta of light

Quantum theory's next steps came from the work of Niels Bohr in Denmark. Bohr was concerned with the structure of atoms, which emit light at specific frequencies that can be carefully measured in the lab. Bohr realised that these specific frequencies could be understood if electrons orbited the atomic nucleus only on special, "quantised" orbits. Like Einstein's quanta of light, these orbits could only have special, quantised energies. Electrons would then (mysteriously) "jump" from one orbit to the other, emitting quanta of light. These are the famous "quantum jumps".

To most physicists, this sounded like black magic. But it worked: with these daring assumptions, Bohr could predict the frequencies of the emitted light correctly. Something of the mystery of the atom appeared to be unravelling.

[The physicist who argues that there are no objective laws of physics](#)

Bohr became a recognised figure. He created an institute in Copenhagen where the best minds of the younger generation began to gather, trying to fully unravel the physics of the atom. Among these visitors was [Werner Heisenberg](#). In the summer of 1925, inspired by Bohr's ideas and taking refuge from a violent attack of hay fever, the 23-year-old Heisenberg spent a few days of solitude on the

wind-scorched island of Helgoland, in the North Sea.

After obsessive and feverish days of intense calculations, mixing up confused ideas, Heisenberg produced an acrobatic calculation that would change the direction of science. He treated the position of an electron not as a single variable, but rather as a table of numbers, with rows and columns indicating the initial and final orbit of a quantum "jump".

Years later, perhaps romanticising, he described himself on the island with these words: "It was around three o'clock in the morning when the results of my calculations were before me. I felt profoundly shaken. I was so agitated that I could not sleep. I left the house and began walking slowly in the dark. I climbed on a rock overlooking the sea at the tip of the island, and waited for the sun to come up..."

The core of quantum mechanics

Back at his home university in Göttingen, Germany, he gave the calculation to his boss, [Max Born](#). Out of Heisenberg's messy calculation, Born saw the key to the new physics: physical quantities aren't described by simple variables. They must be described by more complicated mathematical quantities that "do not commute". This means the multiplication of two quantities gives a different result depending on which comes first. Born divined that the

position X and the momentum P of an electron satisfy the fundamental equation $XP - PX = ih/2\pi$. In this equation, h is the constant that Planck had introduced 25 years earlier – and i is the imaginary unit, the square root of -1.

This obscure oracular equation is the core of [quantum theory](#). It means that if we first measure the position of a particle and then its velocity, we can obtain a result that is different from measuring velocity and position in the opposite order. Position and velocity, therefore, aren't properties of an electron that are exactly simultaneously determined.

Born sent Heisenberg's article to a scientific journal in Heisenberg's name. Then, with the help of Pascual Jordan, a mathematically brilliant assistant also in his early 20s, he published the founding paper of quantum theory, with the new equation, over-generously attributing all the credit to Heisenberg. Many further clarifications and a spectacular number of applications awaited the theory in 1925. But in the articles of Born, Jordan and Heisenberg, quantum theory was already in place.

Can quantum hints in the brain revive a radical consciousness theory?

With anaesthetics and brain organoids, we are finally testing the idea that quantum effects explain consciousness – and the early results suggest this long-derided idea may have been misconstrued

Max Born, in my opinion, deserves the credit for the discovery of quantum theory more than anybody else among the many scientists involved in this grandiose intellectual adventure. He introduced the expression “quantum mechanics”. He divined the founding equation $XP - PX = ih/2\pi$. He is the unsung hero of quantum theory.

A few months later, Wolfgang Pauli showed that not only the frequencies but also the intensities of the light emitted by the atoms could be computed from first principles with the new theory. In a letter to his old friend Michele Besso, Einstein wrote that: "The most interesting theorisation of recent times is that of Heisenberg-Born-Jordan on quantum states: a calculation of real witchery."

For his part, Bohr, the old master, would recall years later: "We had at the time only a vague hope of [being able to arrive at] a reformulation of the theory in which every inappropriate use of classical ideas would be gradually eliminated. Daunted by the difficulty of such a programme, we all felt great admiration for Heisenberg when, at just twenty-three, he managed it in one swoop." Well, Heisenberg... with a little help from his friends. But, perhaps unfortunately, this isn't the end of the story.

Erwin Schrödinger's wavefunction

First, another kid in his early 20s, Paul Dirac, equally realised that Heisenberg's tables were non-commutative variables. He constructed an abstract theory that turned out to be the same as that of the wizards of Göttingen.

Then trouble came. Schrödinger arrived at the same results as Pauli using totally different ideas. His weren't obtained in a university department either: the story goes that he was on

a retreat in the Swiss mountains with a secret lover.

Schrödinger developed an idea introduced in the PhD thesis of the young physicist Louis de Broglie. The thesis, which Einstein had pointed out to him, explored the obscure possibility that electrons – considered at the time to be particles – might also be waves, like Einstein's quanta of light. Schrödinger wondered which equation would be satisfied by these waves, and guessed it. Then, using it in spare moments during his romantic break, he derived the same results regarding the atom that Pauli had obtained with the Göttingen group's theory.

The idea of an electron being just a wave was so simple that it threw the Göttingen group and their esoteric speculations on non-commuting quantities off balance. It seemed like Heisenberg, Born, Jordan and Dirac had built an obscure theory only because they had taken the long and winding road. Things could be made much simpler: the electron is a wave. Waves are easy to visualise. Schrödinger appeared to have triumphed.

But his victory was short-lived. Heisenberg soon realised that the clarity of Schrödinger's waves was a mirage. A wave spreads out, an electron doesn't: when an electron arrives somewhere, it arrives at a single point. The discussion became lively, then virulent. Heisenberg was cutting: "The more I think about the physical aspects of Schrödinger's

theory, the more repellent I find it. When he [Schrödinger] writes about the visualization of his theory being probably not completely correct, it is tantamount to saying that it is idiotic". Schrödinger tried to retort wittily: "I cannot imagine an electron leaping about, here and there, like a flea."

Max Born's Nobel prize

Heisenberg was right. Wave mechanics is no clearer than the non-commutative abacus of Göttingen. Years later, Schrödinger, who was to become one of the most acute thinkers on the strangeness of quanta, recognised defeat. "There was a moment," he writes, "when the creators of wave mechanics [that is, himself] nurtured the illusion of having eliminated the discontinuities in quantum theory. But the discontinuities eliminated from the equations of the theory reappear the moment the theory is confronted with what we observe."

Born was awarded the Nobel prize much later, in 1954, and only for "the statistical interpretation of the wave function". Why so late? Why was he not recognised for his monumental 1925 contribution? He had already arrived at full quantum mechanics, its basic formula $XP - PX = ih/2\pi$, and he had uncovered this statistical interpretation before Schrödinger's wave function. Maybe Pascual Jordan's Nazi sympathies played a role: he co-authored the two papers where quantum mechanics is defined, and after the second world

war, it might have been difficult to award a Nobel prize to him.

In a 2023 [paper](#) I wrote with the historian of science John Heilbron, we analysed the historical developments that led to quantum theory, and we observed that in the history of science, like always in history, the evaluation of the past evolves as ideas change in the present.

[Carlo Rovelli on the bizarre world of relational quantum mechanics](#)

[Physicist Carlo Rovelli explains the strange principles of relational quantum mechanics – which says objects don't exist in their own right – and how it could unlock major](#)

[progress in fundamental physics](#)

What quantum phenomena tell us about reality is still debated (see [“What does quantum theory really tell us about the nature of reality?”](#)). There are various interpretations. I think that Schrödinger’s waves are only a mathematical representation of the information that a physical system has about another. This reading of quantum phenomena is called “relational”, because it emphasises that [we can only describe how systems affect one another](#), not how they are in isolation. In other interpretations, such as “[QBism](#)”, quantum states only code our own knowledge of a system.

In light of these ideas, it is clear to me that Schrödinger’s waves obscured, rather than clarified, the theory developed by Göttingen’s wizards and Dirac. It misled the community into viewing quantum theory as a revelation about mysterious waves (or mysterious “quantum states”), instead of reading it in the straightforward Göttingen way: a theory of the probabilities of the manifestations of a system to any other system.

I think what quantum phenomena tell us is that the world is genuinely probabilistic and granular at the scale fixed by the Planck constant, and that reality is constituted by manifestations of physical systems to one another. This is captured in the words of Niels Bohr: “In quantum physics the interaction with the measuring apparatus is an inseparable

part of the phenomenon. The unambiguous description of a quantum phenomenon is required in principle to include a description of all the relevant aspects of the experimental arrangement."

Little about this idea needs to be changed, a century later: all that is required is to replace "the measuring apparatus" with "any other physical system" the object is interacting with. The world is the ensemble of ways that physical systems affect one another. This is what quantum physics seems to me to be about. That is quantum mechanics as Max Born, the scientist who named it, had conceived it.

What is quantum theory?

The founding principle of quantum theory isn't too complicated. To get your head around it, imagine how you might turn the volume knob on an old-fashioned stereo and hear the sound get gradually louder. Quantum theory says that the properties of particles, such as their energy, don't vary in this way. Instead, they can only take on certain discrete values. Think more of turning up the heating on a thermostat, moving from one degree to another with no transition between. This assumption about how particles work turns out to be a far superior way to explain reality (see main stories).

The problems start with how the theory works in practice. It

provides a probability for what you will find when you measure a particle, but it says nothing about what it is doing beforehand. How to interpret this has confused us from the start. And over the years, we have also discovered that quantum particles behave in deeply strange ways. They sometimes seem to act more like waves, for instance. Pairs of them can be entangled, meaning they can apparently influence each other's properties even when separated by vast distances. They can also adopt a superposition, being in two places or taking two paths at once.

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