hominin called *Paranthropus*. (*Paranthropus* specimens were found more than a decade after Dart described Taung.) This finding is consistent with a study of fossil foot bones that concluded that different species of early hominin evolved distinct ways of walking[15].

Future researchers who want to find out how the shift to full-time bipedalism and the accompanying emergence of childhood happened in our ancestors would do well to examine how bipedalism developed in various hominin species by comparing not just their skulls and feet, but also the bones in the rest of the skeleton at different stages of life history. Happily, methods are being developed that enable scientists to assess changes inside bones during the development of locomotion as humans[16] and other young apes[17] mature. Comparative studies of motor reflexes in developing humans and other apes could also help[18].

A job well done

Nearly 40 years ago, the first computed tomography study[5] of Taung's developing dentition concluded that "the Taung 'child' is not a little human, but just as important, it is not a little ape". Today it seems that the Taung 'child' was probably not a child, but was a weanling instead[6].

I think Dart would have been surprised and pleased at this revelation and the enormous amount of research that his discovery is continuing to stimulate 100 years after he described Taung in *Nature*. Happy birthday, Taung!

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WIKTOR MAZIN, QUANTUM FRACTAL ARTIST

A fractal image generated using a quantum computer, by artist Wiktor Mazin.

What does quantum theory really mean?

A century on, physicists still can't agree what our most fundamental picture of reality tells us. **By Sean Carroll**

Everyone has their favourite example of a trick that reliably gets a certain job done, even if they don't really understand why. Back in the day, it might have been slapping the top of your television set when the picture went fuzzy. Today, it might be turning your computer off and on again.

Quantum mechanics — the most successful and important theory in modern physics — is like that. It works wonderfully, explaining things from lasers and chemistry to the Higgs boson and the stability of matter. But physicists don't know why. Or at least, if some of us think we know why, most others don't agree.

The singular feature of quantum theory is that the way we describe physical systems is distinct from what we see when we observe them. The textbook rules of quantum mechanics therefore need to invoke special processes to describe 'measurement' or 'observation', unlike every previous framework for physics. As a field, physics does not have any consensus on why that is the case, or what it even means.

The first hints of quantum behaviour in nature came in works by physicists Max Planck in 1900 and Albert Einstein in 1905. They showed that certain properties of light could best be explained by imagining that it came in discrete, particle-like chunks, rather than as the smooth waves that classical electromagnetism depicts. But their ideas fell short of describing a complete theory. It was the German physicist Werner Heisenberg who, in 1925, first put forward a comprehensive version of quantum mechanics. Later that year, Max Born and Pascual Jordan followed up on that with Heisenberg, and Erwin Schrödinger soon produced an independent formulation of the theory[1].

So it is fair to celebrate 2025 as the true centenary of quantum theory. Although such a commemoration can rightly point to a wide variety of breathtaking experimental successes, it must leave room to acknowledge the foundational questions that remain unanswered. Quantum mechanics is a beautiful castle, and it would be nice to be reassured that it is not built on sand.

Break from the past

Ever since Isaac Newton formulated classical mechanics in the seventeenth century, theories of physics have followed a definite pattern. You have a system under consideration: perhaps a planet orbiting a star, or an electric field or a box of gas. At any one moment in time, the system is described by its 'state', which includes both the system's current configuration and its rate of change; for a featureless single particle, this amounts to its position and velocity (or, equivalently, momentum). Then, you have equations of motion, which tell us how the system will evolve, given its present state. This basic recipe worked for everything from Newtonian gravity right up to Einstein's theories of relativity, which, like quantum theory, are a product of the early twentieth century. But with the advent of quantum mechanics, the recipe suddenly failed.

The failure of the classical paradigm can be traced to a single, provocative concept: measurement. The importance of the idea and practice of measurement has been acknowledged by working scientists as long as there have been working scientists. But in pre-quantum theories, the basic concept was taken for granted. Whatever physically real quantities a theory postulated were assumed to have some specific values in any particular situation. If you wanted to, you could go and measure them. If you were a sloppy experimentalist, you might have significant measurement errors, or disturb the system while measuring it, but these weren't ineluctable features of physics itself. By trying harder, you could measure things as delicately and precisely as you wished, at least as far as the laws of physics were concerned.

Quantum mechanics tells a very different story. Whereas in classical physics, a particle such as an electron has a real, objective position and momentum at any given moment, in quantum mechanics, those quantities don't, in general, 'exist' in any objective way before that measurement. Position and momentum are things that can be observed, but they are not pre-existing facts. That is quite a distinction. The most vivid implication of this situation is Heisenberg's uncertainty principle, introduced in 1927, which says that there is no state an electron can be in for which we can perfectly predict both its position and its momentum ahead of time[2].

Instead, quantum theory describes the state of a system in terms of a wavefunction, a concept introduced[3] by Schrödinger in 1926, together with his eponymous equation that describes how the system changes over time. For our single electron, the wavefunction is a number assigned to every position we might observe the electron to be in — a wave, in other words, that might be mostly localized near an atomic nucleus or spread widely throughout space.

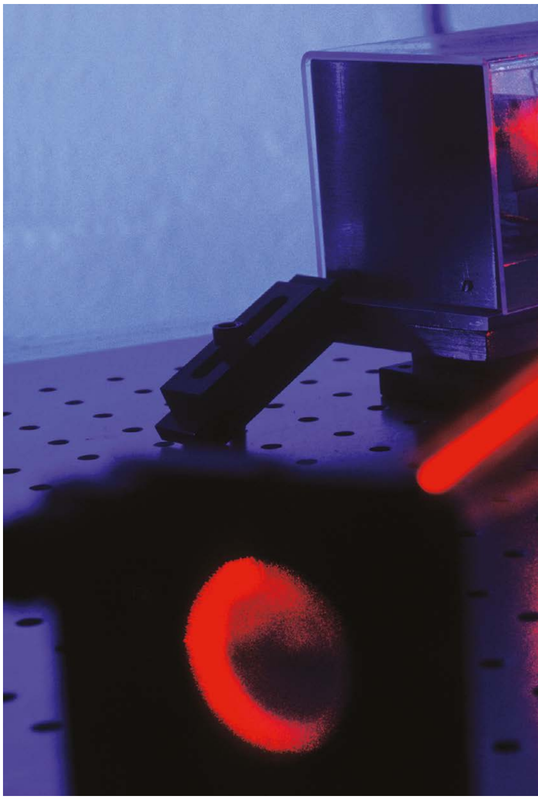
Where things get tricky is in the relationship between the wavefunction and observable quantities, such as position and momentum, that we might want to measure. The answer was suggested[4] by Born soon after Schrödinger's original paper. According to Born's interpretation, we can never precisely predict the outcome of a quantum measurement. Instead, we can determine the probability of getting any particular outcome for an electron's position, say, by calculating the square of the wavefunction at that position. This recipe completely overturned the ideal of a deterministic, clockwork universe that had held sway since Newton's time.

In retrospect, it is impressive how quickly some physicists were able to accept this shift. Some, not all. Luminaries such as Einstein and Schrödinger were unsatisfied with the new quantum consensus. It's not that they didn't understand it, but that they thought the new rules must be stepping stones to an even more comprehensive theory.

The appearance of indeterminism is often depicted as their major objection to quantum theory — "God doesn't play dice with the Universe", in Einstein's memorable phrase. But the real worries ran deeper. Einstein in particular cared about locality, the idea that the world consists of things existing at specific locations in space-time, interacting directly with nearby things. He was also concerned about realism, the idea that the concepts in physics map onto truly existing features of the world, rather than being mere calculational conveniences.

> **"The failure of the classical paradigm of physics can be traced to a single, provocative concept: measurement."**

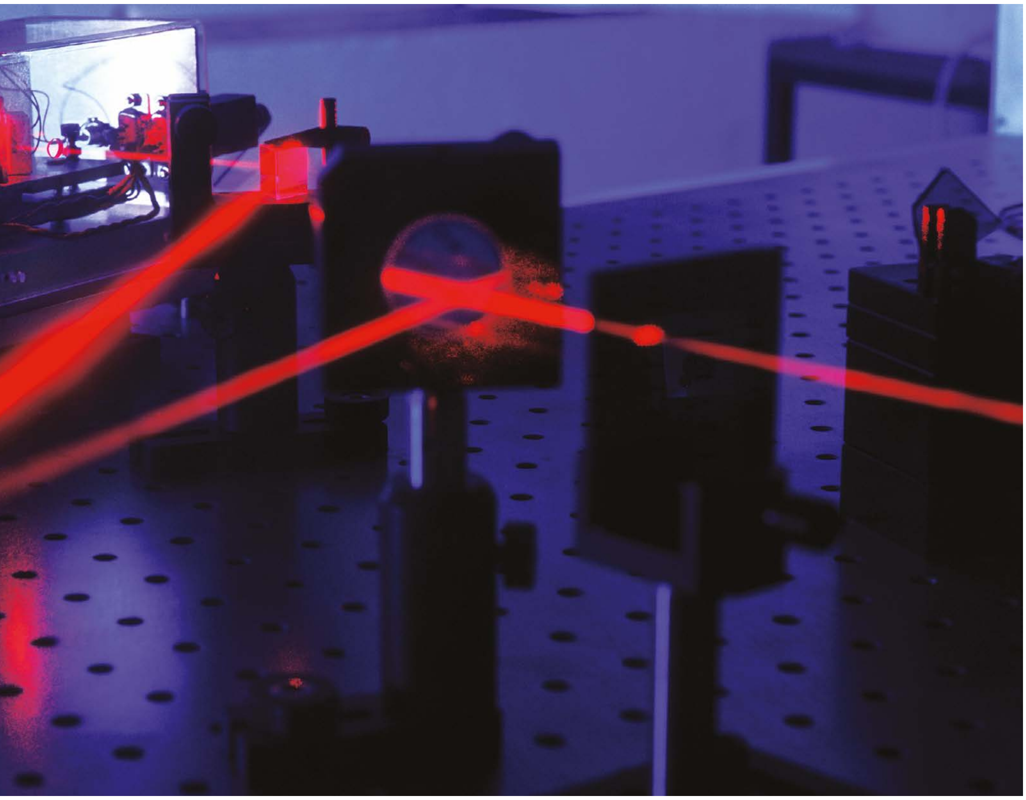
Einstein's sharpest critique appeared in the famous EPR paper[5] of 1935 — named after him and his co-authors Boris Podolsky and Nathan Rosen — with the title 'can quantum-mechanical description of physical reality be considered complete?'. The authors answered this question in the negative, on the basis of a crucial quantum phenomenon they highlighted that became known as entanglement.



If we have a single particle, the wavefunction assigns a number to every possible position it might have. According to Born's rule, the probability of observing that position is the square of the number. But if we have two particles, we don't have two wavefunctions; quantum mechanics gives a single number to every possible simultaneous configuration of the two-particle system. As we consider larger and larger systems, they continue to be described by a single wavefunction, all the way up to the wavefunction of the entire Universe.

As a result, the probability of observing one particle to be somewhere can depend on where we observe another particle to be, and this remains true no matter how far apart they are. The EPR analysis shows that we could have one particle here on Earth and another on a planet light years away, and our prediction for what we would measure about the faraway particle could be 'immediately' affected by what we measure about the nearby particle.

The scare quotes serve to remind us that, according to the special theory of relativity, even the concept of 'at the same time' isn't well defined for points far apart in space, as



Laser experiments have probed the reality of quantum entanglement, a concept alien to intuitive conceptions of how physics should work.

PASCAL GOETGHELUCK/SPL

Einstein knew better than anyone. Entanglement seems to go against the precepts of special relativity by implying that information travels faster than light — how else can the distant particle 'know' that we have just performed a measurement?

We can't actually use entanglement to communicate across great distances. Measuring our quantum particle here, we now know something about what will be observed far away, but anyone who is actually far away doesn't have access to the knowledge we have, so no communication has occurred. But there is at least a certain tension between how quantum theory describes the world and how we think space-time works in Einsteinian relativity.

Reclaiming reality

Attempts to resolve this tension have proliferated, with no clear consensus in sight. Indeed, significant disagreement lingers around the most central question we can think of: is the quantum wavefunction supposed to represent reality, or is it just a tool we use to calculate the probability of experimental outcomes? This issue fundamentally divided Einstein and the Danish physicist Niels Bohr in famous debates they had over decades about the meaning of quantum mechanics. Einstein, like Schrödinger, was a thoroughgoing realist: he wanted his theories to describe something we might recognize as physical reality. Bohr, along with Heisenberg, was willing to forgo any talk about what was 'really happening', focusing instead on making predictions for what will happen when something is measured.

The latter perspective gave rise to 'epistemic' interpretations of quantum theory. The views of Bohr and Heisenberg came to be known as the Copenhagen interpretation, which is very close to what physicists teach in textbooks today. Modern versions include QBism[6], short for 'quantum Bayesianism', and relational quantum mechanics[7]. Both of these interpretations emphasize how quantum states shouldn't be considered in their own right, but only relative to an observer, the process of measuring and the changing states of knowledge during that process.

A nice thing about epistemic approaches is that worries about faster-than-light influences evaporate. When an observer takes a measurement, they update their knowledge; nothing physically travels from one entangled particle to another. A downside is that these approaches completely leave open the question of what reality truly is, which is (or should be, one presumes) important to physics. This is especially problematic given that the wavefunction certainly acts like a physical thing under certain circumstances. For example, the wavefunction can interfere with itself, as demonstrated in the double-slit experiment. A wavefunction that passes through two narrow slits, recombining on the other side, will constructively or destructively interfere depending on the oscillations of the wave. That certainly sounds like the behaviour of a real physical thing.

The alternative is an ontic approach, accepting that the quantum state represents reality (at least in part). The problem there is that we never 'see' the wavefunction itself; we only use it to make predictions for what we do see. We can think of the wavefunction as representing a superposition of many possible measurement outcomes. But is hard to resist, once we have made a measurement and recorded an outcome, thinking of that result as what is real, not the abstract superposition of possibilities that preceded it.

There are a number of ontic models of quantum mechanics that reconcile the centrality of wavefunctions with their tricky relationship to observations. In pilot-wave or hidden-variable models, first developed comprehensively[8,9] by David Bohm in the early 1950s, wavefunctions are real but there are also extra degrees of freedom representing the actual positions of particles, and it is the latter that get observed. In the Everettian, or many-worlds, interpretation, introduced by Hugh Everett a little later[10], observers become entangled with the systems they measure, and every allowed outcome is realized in separate branches of the wavefunction, which are interpreted as parallel worlds. In objective-collapse models of varying flavours[11,12], the wavefunction occasionally adjusts itself (in violation of the conventional Schrödinger equation) to look like the semiclassical reality we observe.

Although these approaches are often thought of as competing interpretations of quantum mechanics, this is a misconception, because they are distinct physical theories. Objective-collapse models have a variety of explicit experimental consequences; most dramatically, by violating the principle of energy conservation when the wavefunction objectively collapses, something that might be observable in ultra-cold atomic systems. Tests are ongoing, but no evidence for these effects has yet been found. As far as anyone knows, there is no experiment that could distinguish between pilot-wave and Everettian approaches. (Advocates of each tend to argue that the other is simply ill defined.)

So, physicists don't agree on what precisely a measurement is, whether wavefunctions represent physical reality, whether there are physical variables in addition to the wavefunction or whether the wavefunction always obeys the Schrödinger equation. Despite all this, modern quantum mechanics has given us some of the most precisely tested predictions in all of science, with agreement between theory and experiment stretching to many decimal places.

The theory of relativistic quantum fields, the basis of all of modern particle physics, must count among the greatest successes of quantum mechanics. To accommodate the observed fact that particles can be created or destroyed, along with the symmetries of relativity, its starting point is quantum fields stretching through all of space. The rules of quantum theory imply that small vibrations in such fields naturally seem to be collections of individual particles. The iterated influences of these vibrations on each other lead to a plethora of observable phenomena that have fantastically been confirmed by experiment, from how quarks are confined to make protons and neutrons, to the existence of the Higgs boson. This particle arises from vibrations in a Higgs field suffusing all of space, which gives mass to other particles and explains why the weak nuclear force has such a short range. According to the cosmological inflation theory, the origin of stars and galaxies might even be traced to tiny quantum variations in the density of the early Universe.

Not all there

But for all its successes, quantum field theory has its own puzzles. Infamously, a straightforward calculation of the quantum corrections to the scattering probability of two particles often results in infinitely large answers — not a feature you want a probability to have. Modern physics has come to terms with this issue by using 'effective field theories', which attempt to describe processes only at (relatively) low energies and momenta, and from which the troublesome infinities are entirely absent.

But this framework still leaves us with problems of 'naturalness'. In the effective-field-theory approach, parameters we observe at low energies represent the combined effects of unobservable processes at very high energies. This understanding allows us to predict what natural values should be for parameters such as the Higgs mass or the energy density of the vacuum. But the observed values of these numbers are much lower than expected — a problem that still awaits convincing solution.

Then, there is the largest problem of all: the difficulty of constructing a fundamental quantum theory of gravity and curved space-time. Most researchers in the field imagine that quantum mechanics itself does not need any modification; we simply need to work out how to fit curved space-time into the story in a consistent way. But we seem to be far away from this goal.

Meanwhile, the myriad manifestations of quantum theory continue to find application in an increasing number of relatively down-to-Earth technologies. Quantum chemistry is opening avenues in the design of advanced pharmaceuticals, exotic materials and energy storage. Quantum metrology and sensing are enabling measurements of physical quantities with unprecedented precision, up to and including the detection of the tiny rocking of a pendulum caused by a passing gravitational wave generated by black holes one billion light-years away. And of course, quantum computers hold out the promise of performing certain calculations at speeds that would be impossible if the world ran by classical principles.

All of this has happened without any complete agreement on how quantum mechanics, at its core, actually works. Historically, advances in technology have often facilitated — or even necessitated — improvements in foundational understanding. We are continually inventing new ways to smack the television set called reality, remaining optimistic that a fuzzy picture will eventually snap into focus.

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Niels Bohr (left) and Albert Einstein (second from right), pictured with fellow physicists James Franck (seated) and Isidor Rabi.

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NASA's 'most prolific planet hunter so far'

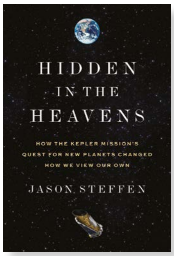
Ingenuity and decades of planning enabled the success of the Kepler Space Telescope. **By Elizabeth Tasker**

In the mid-1980s, NASA engineer William Borucki faced a panel of in-house specialists. They told him to either justify an idea that many were calling crazy, or quit. His concept was for a space telescope dedicated to detecting extrasolar planets, or exoplanets, which orbit stars other than the Sun. It was an audacious idea, a decade before any such planets had been found.

Borucki had been developing the concept since the 1970s and was under pressure to stop wasting NASA resources. Yet he managed to convince the panel to let him carry on, and even persuaded several members to join him. Still, it would take until 2001 for the mission to be signed off, and another eight years before Borucki's crazy idea sat on the launchpad.

That spacecraft, the Kepler Space Telescope, remains humanity's most prolific planet hunter so far, having spied thousands of distant planets and many more candidate ones. In *Hidden in the Heavens*, astrophysicist Jason Steffen — who joined the mission a year before it launched in 2009 — relates the story of Kepler and its surprising discoveries.

Kepler detected planets by identifying the dimming of light from a star as a planet moved across its face. Doing this is extremely hard — Steffen compares the process to looking down at Las Vegas from space and searching for a fly buzzing around a street light. The Kepler team had to prove that the telescope's instruments



Hidden in the Heavens: How the Kepler Mission's Quest for New Planets Changed How We View Our Own
Jason Steffen
Princeton Univ. Press (2024)