The quantum centennial

One hundred years ago, a simple concept changed our world view forever.

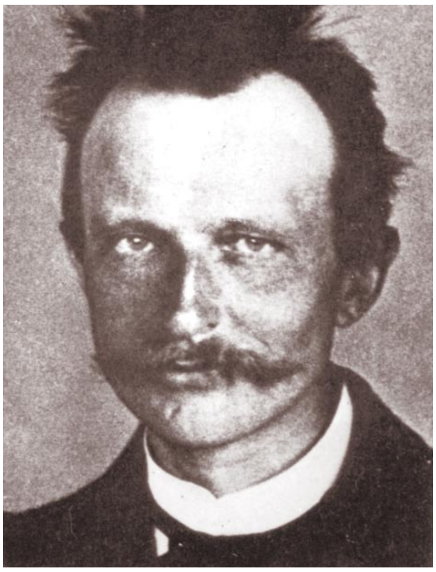
Anton Zeilinger

When Max Planck announced his quantum assumption in his talk at the German Physical Society in Berlin on 14 December 1900, nobody, including himself, realized that he was opening the door to a completely new theoretical description of nature. Quantum physics has had unsurpassed success in explaining many phenomena — from the structure of elementary particles, through the essence of chemical bonds or the nature of many solid-state phenomena, all the way to the physics of the early Universe. To date, all experiments magnificently confirm all quantum predictions with impressive precision.

Quantum mechanics also led to an immense number of technological applications. Modern high-tech developments would have been inconceivable without it — lasers and semiconductors are just two such examples. But most significantly, quantum mechanics changed our view of the world in a way that was completely surprising and had unprecedented depth.

Born in 1858 and educated in Munich and Berlin, Planck became interested in thermodynamics early in his career. In 1894, a very basic problem captured his attention: how to explain the colours emitted by glowing bodies. The classical explanation of the period worked well for the short parts of the light spectrum, but did not agree with experiments for all wavelengths. Planck had the advantage of close access to the most recent experimental results obtained by Otto Lummer and Ernst Pringsheim and by Ferdinand Kurlbaum and Heinrich Rubens, also working in Berlin, on the spectral distribution of black-body heat radiation emerging from a hole in a box kept at a certain temperature.

Planck eventually found a full explanation, but only after forcing himself "to an act of despair" by assuming that energy can only be exchanged between the light field inside the box and the walls of the container in discrete quanta, multiples of the energy $E = h\nu$, where ν is the light's frequency and h is now called Planck's constant. Planck tried unsuccessfully for many years to find an alternative derivation of this experimentally successful radiation law from other known laws of physics, but he slowly had to accept that he had found something fundamentally new.



ARCHIV ZUR GESCHICHTE DER MAX-PLANCK-GESELLSCHAFT, BERLIN-DAHLEM

A new beginning: in 1900 Max Planck (right) articulated the concept that underpins quantum theory and that sparked debate between Einstein and Bohr at the 1927 Solvay congress (below).

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The next important step in the early days of quantum mechanics came in 1905, when Albert Einstein introduced his radical hypothesis of quanta of light to explain the photoelectric effect. For a while, this remained the only significant instance of the quantum being taken seriously. Einstein's hypothesis met with strong objections from his contemporaries, including Planck himself. As late as 1913, Planck, together with his fellow physicists Heinrich Rubens, Walther Nernst and Emil Warburg, wrote in a recommendation letter for Einstein's election to the Prussian Academy of Sciences: "One should not hold against him too much that in his speculations he might have occasionally overshot the goal, as for example in his hypothesis of the quanta of light." Ironically, it was this hypothesis that gained Einstein the physics Nobel prize in 1921, three years after Planck had received it.

A change of perspective

It was also Einstein who first realized that the quantum hypothesis would lead to a major change in our view of the world, particularly by giving randomness a new and much more fundamental role than before. This discussion about interpreting quantum mechanics — which occupied the minds of many leaders in the field, especially after the formulation of modern quantum mechanics by Werner Heisenberg and Erwin Schrödinger in 1925–1926 — is still going to this day.

Heisenberg's matrix mechanics of 1925 and Schrödinger's wave mechanics of 1926, soon found to be equivalent theoretical descriptions of quantum phenomena, launched probably the most successful period of theoretical science in human history. In atomic physics, energy levels in atoms could at last be explained. And later, with the introduction of group theory into quantum mechanics, this explanation was extended even to complicated molecules. At the same time, simple molecules could be described quantitatively, and there were enormous successes in applying quantum mechanics to the solid state.

Hans Bethe, in his article "Quantum theory" in *More Things in Heaven and Earth*, celebrating the centennial of the American Physical Society in 1999, wrote: "1926, the year when I started graduate work, was a wonderful year for theoretical physicists. Whatever problem you tackled with the new tools of quantum mechanics could be successfully solved, and hundreds of problems, from the experimental work of many decades, were around, asking to be tackled."

Another important discovery in 1925 was Pauli's exclusion principle, which says that no two electrons can occupy the same quantum state. This principle plays a central role in many fields — for example in solid-state physics it helps explain the electrical conductivity of metals. It also tells us why chemical elements are so different. Modern quantum theory then entered a stage of maturity over the next two years, during which Paul Dirac developed the quantum theory of the electromagnetic field, the mother of all modern field theories, which are so important in the physics of elementary particles, and the relativistic quantum theory of the electron, which predicts the existence of antimatter.

The discussion of the philosophical interpretation of quantum mechanics continued in parallel with the enormous successes of the new theory. It culminated in the famous debate between Einstein and Niels Bohr, which began at the Solvay congresses of 1927 and 1930 and continued later in writing because of Einstein's emigration from Nazi Germany. Using a series of elegant *Gedanken* experiments — thought experiments — Einstein initially tried to show that quantum mechanics is inconsistent, in that it is possible to extract from an individual quantum phenomenon more information than is described by the limit represented by the Heisenberg uncertainty relation. Yet, in all instances, Bohr showed that consequent application of the new quantum laws avoided any contradictions.

Intellectual tug-of-war

Although Einstein clearly did not have the upper hand in his debate with Bohr, it is very much to his credit that he was one of the few who saw that quantum physics fundamentally challenges our view of the world. This is because it forces us to give up what can be called the naive classical realism so central not only to the views of physicists but also part of our approach to, and interpretation of, everyday life.

Finally, the famous Einstein–Podolsky–Rosen paper of 1935 introduced the idea of pairs of particles strongly correlated over large distances. Einstein had thought that these correlations would be a last-ditch stand of classical realism, because they hint at a possible classical model. But his hope to explain them using hidden properties of the individual systems was shown by John Bell in 1964 to lead to predictions that are in conflict with quantum mechanics. In fact, Schrödinger had realized in 1935 that such correlated systems are extremely non-classical. He coined the term 'entanglement' for these correlations and he called them "the essential characteristic" of quantum mechanics.

FROM LEWIS CARROLL'S *ALICE'S ADVENTURES IN WONDERLAND*

Here and not here: the Cheshire cat may have been the first observation of macroscopic superposition.

Technological progress since then has led to the possibility of performing not only many of the early *Gedanken* experiments but also a plethora of new ones. Most significantly, it is now possible to do real, detailed experiments with individual quantum systems such as individual photons, electrons, positrons, neutrons and atoms (even some made of antimatter) and molecules as large as fullerenes. Quantum experiments with more complicated systems have also become routine, where particles are entangled with each other just as originally postulated by Einstein, Boris Podolsky and Nathan Rosen. All modern experiments confirm the quantum predictions with unprecedented precision. And so, although one tiny loophole still remains for advocates of a classical world view, the evidence overwhelmingly suggests that a local realistic explanation of nature is not possible.

But the story does not stop here. As often in the history of physics, investigation of fundamentals has given rise to a new field. This fledgling field, which can be called the physics of quantum information, deals with the novel possibilities of encoding, transmitting and processing information through individual and entangled quantum systems. Quantum cryptography promises to provide us with a communication technology guaranteed to be secure against eavesdropping. Quantum teleportation can be seen as the possibility of directly transferring information from one system to another without that information first being read out and then transmitted by travelling on some carrier. And, as the most ambitious long-term goal, the quantum computer, if ever built, would give us novel computational techniques of unprecedented speed.

Although it is impossible to predict how a future quantum information technology will look, it is probably a safe bet that quantum laws will be directly relevant for communicating and processing information. This is because technological progress means that fewer and fewer electrons are needed to switch an individual bit in modern microprocessor chips — this is enshrined in Moore's law, which says that the number of transistors on a chip doubles every 18 months. If this law continues to hold unabated, we will reach the quantum realm in about 20 years, when an individual bit is carried by just one electron.

The big increase in activity in fundamental experiments over the past two decades has also renewed the debate about the interpretation of the theory. Richard Feynman once commented, "I think I can safely say that nobody today understands quantum mechanics", and Sir Roger Penrose remarked that, although the theory agrees very well with all experiments and it is of profound mathematical beauty, it "makes absolutely no sense". So, where is the problem, if the theory fits all experimental results so nicely? The problem arises when we dare to ask what quantum mechanics might mean for our view of the world (*Weltanschauung*) in a broad sense. Can we safely, as many do, restrict the counterintuitive notions of quantum mechanics such as quantum superposition and entanglement to the microscopic world?

An absurd idea?

Schrödinger formulated his famous cat paradox in 1935, just to show how absurd the consequences of quantum mechanics are if applied to macroscopic or even living objects. We all know that a cat cannot be alive and dead at the same time as we never experience such a thing in everyday life.

Although the literature abounds with papers arguing that for one reason or another we may never expect to see superpositions of macroscopic objects, it might very well be that we should replace 'never' by 'not yet'. After all, who knows what experimental progress will bring in the next century, let alone the next millennium. And who knows what clever tricks our theoretical colleagues will find to circumvent the arguments currently put forward against the possibility of observing macroscopic superpositions. It is a safe bet that the research programme to demonstrate quantum phenomena for objects of increasing size and complexity will turn out to be one of the most interesting and

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hopefully fruitful avenues of research.

Even with the observation of macroscopic superposition still far away, many physicists are already puzzling over the so-called quantum measurement problem. This is the fact that although quantum mechanics makes perfectly valid predictions for statistical ensembles, in general it is not possible to make definite predictions for individual events, or, as John Bell put it, quantum mechanics does not explain "why events happen". In the case of Schrödinger's cat, even if we accept that the cat might be in a superposition state of 'live' and 'dead', there is no way to explain why, in a specific run of the experiments, we observe the specific outcome 'alive' or 'dead'. We can only give their probabilities. This measurement problem has elicited many different responses from within the physics community.

One resolution to the problem suggested by some, for example Ghirardi, Rimini and Weber, and Pearle, modifies the evolution laws of quantum mechanics so that they become non-linear. But if measurements are precise enough, this will turn out to be in conflict with the predictions of standard quantum mechanics, which is linear. I venture that all future experiments will confirm the quantum predictions and thus result in conflict with nature for such non-linear theories.

Some interpretations try to define the problem away. These include the Many-Worlds interpretation, which assumes that all measurement results coexist in split universes. Another possible position is Bohm's viewpoint, where particles actually have well-defined positions and momenta at all times but move in a quantum potential as a consequence of the Schrödinger equation. This latter point of view makes the same predictions as the standard theory and so does not teach us much that is new.

In the interpretive discussion, the early leaders in the development of quantum mechanics all had their individual points of view. For example, Dirac did not see such discussions as relevant, Schrödinger and Planck were realists, and others had rather unconventional points of view. To Heisenberg the roots of the problem were that the Cartesian divide — the separation between *res cogitans* (that which thinks) and *res extensa* (that which is out there) — had deeply penetrated the human soul during the three centuries after Descartes. For Heisenberg, this was why the epistemological paradigm on which one could build the foundations of quantum mechanics had not been found yet. And Pauli even feels that here we have a recurrence of the medieval "*anima mundi*" (the soul of the world).

An informative theory

Notwithstanding the fact that there are a number of other interpretations, all with their own enthusiastic supporters, it seems that the measurement problem is trying to tell us something interesting.

One of the most careful thinkers on this matter, although not easily understood, is again Niels Bohr, who said: "There is no quantum world, there is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."

Continuing Bohr's line of thinking, it is suggestive to view quantum mechanics as a theory of information. Then the quantum state is just the representation of the information we have in a given situation. In general, the laws of quantum mechanics just permit us to make probabilistic predictions for possible future measurement results. In measurement, simply by observing an experimental result, we obtain novel information and so have to change the representation of our information, the quantum state. The fundamental laws themselves, such as the Schrödinger equation, are just expressions of conservation of information. But this makes a number of questions moot and just a matter of speculation. There are questions which make absolutely no sense — for example, through which of the two slits a particle passes when the double-slit interference experiment is observed, or whether Schrödinger's cat really is alive or not.

It thus appears that after one century of quantum mechanics we have fascinating parallel developments. On the one hand we have new ways of processing information using quantum mechanical laws. On the other hand we are gaining new insight into quantum mechanics itself by viewing it as an advanced theory of information.

One important open question is whether or not the laws of quantum mechanics will ever be found to play a significant role in biological systems, besides the obvious one of explaining their chemistry. In other words, have biological systems been selected by evolution to avoid the quantum domain so that they do not run into the problems of randomness, uncertainty and indefiniteness encountered there? Or are there at least some instances where biological systems can make use of the positive features such as quantum entanglement and quantum superposition? Clearly, this question is related to the one discussed above — is there an upper limit for the scale on which quantum phenomena can be shown to appear? In its most ambitious form this question asks whether the quantum might play any role in an understanding of mind.

Further pondering the future of quantum mechanics, it is probably safe to say that its basic rules are simple enough to be robust against change for a long time, if not for ever. Among these basic principles are the use of probability amplitudes whose squares give probabilities and which are superposed in a linear way, or the Pauli principle. Also, the mathematical beauty of the theory is a strong argument for its robustness.

At another frontier, the programme to quantify gravity (see accompanying article by Giovanni Amelino-Camelia on page 661), that aims to arrive at a description of space and time consistent with quantum mechanics, for some physicists points to the necessity for a deep revision of our foundations.

If anything is certain then it is the fact that physics will be completely different 100 years from now. Suggestions made today by some that we are close to an end of science or close to finding the final theory will be as much demonstrations of the limitations of human imagination as similar suggestions made in the nineteenth century. Then, for example, Max Planck was told in 1874 by the Munich physicist Philipp von Jolly to study something else, as all fundamental laws were known and all that was left to physicists was to fill in a few remaining details. ■

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Further reading

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2. Bederson, B. (ed.) *More Things in Heaven and Earth: A Celebration of Physics at the Millenium* (Springer, New York, 1999).
3. Amelino-Camelia, G. *Nature* **408,** 661–664 (2000).
4. Schilpp, P. A. (ed.) *Albert Einstein: Philosopher-Scientist* (Open Court, La Salle, 1949).
5. Jammer, M. *The Philosophy of Quantum Mechanics* (Wiley, New York, 1974).
6. Wheeler, J. A. & Zurek, W.H., *Quantum Theory and Measurement* (Princeton Univ. Press, 1983).