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Quantum mechanics at 100: an unfinished revolution

A century ago, physics underwent a change in perspective that was as consequential for the physical sciences as the theory of evolution by natural selection was for biology.

It is rare for a scientific idea or theory to fundamentally change our perspective on reality. One such revolutionary moment is being celebrated in 2025, which the United Nations has declared to be the International Year of Quantum Science and Technology. This marks the centenary of the advent of quantum mechanics, which began in a flurry of papers 100 years ago. Just as it would be impossible to make sense of modern biology without Charles Darwin's theory of evolution, our fundamental understanding of the physical world is now rooted in quantum principles. Modern physics is quantum physics.

The word quantum refers to the way matter absorbs or releases energy – in discrete packets, or quanta. Its use in physics comes from the German word *quant*, which is derived from a Latin term meaning 'how much'. In around 1900, physicists such as Max Planck and Albert Einstein began to describe, in an ad hoc way, why several phenomena of the subatomic realm could not be explained using the classical mechanics developed by Isaac Newton and others some two centuries earlier. Then, in 1925, quantum came to be used to describe the fundamentals of an entirely new form of mechanics – the branch of physics that describes the relationship between forces and the motion of physical objects.

As science historian Kristian Camilleri describes in an Essay on the startling developments of that year and those that followed (see page 269), the physicist Werner Heisenberg travelled to the German island of Heligoland in the North Sea in the summer of 1925 in search of relief from severe hay fever. Shortly after this, he submitted to the journal *Zeitschrift für Physik* a paper whose title translates as 'On quantum-theoretical reinterpretation of kinematic and mechanical relationships' (W. Heisenberg *Z. Physik* **33**, 879–893; 1925). This prompted further studies in the following months by Heisenberg and his close collaborators, as well as work using an alternative approach by Erwin Schrödinger.

The revolution did not begin with physicists throwing away the laws of classical mechanics, but with their radically reinterpreting classical concepts such as energy and momentum. However, it did require its initiators to abandon dearly held common-sense ideas – for example, the expectation that subatomic objects such as particles have a well-defined position and momentum at any given time. Instead, the physicists found that natural phenomena had an inherently unknowable nature. Classical physics, in other words, is only an approximate representation of reality, and manifests itself only at the macroscopic level. A century on, this insight into the nature of the physical world still thrills and bamboozles in equal measures. Many *Nature* readers will know about the philosophical quandaries raised by quantum cats that are simultaneously dead and alive, and about the industry that is growing around quantum computing.

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Others will know how quantum ideas gave rise to the lasers that beam information through the cables of the Internet, and the transistors that provide the processing power of electronic chips. But quantum ideas also shape our understanding of nature, at all levels, explaining why solid objects don't fall apart and how stars shine and, ultimately, die.

A quantum year

Commemorative events are being planned all over the world for the coming 12 months. They include an opening ceremony for the UN year at the headquarters of the UN scientific organization UNESCO in Paris in February; special events at a meeting of the American Physical Society in Anaheim, California, in March; and a workshop for physicists on Heligoland in June. The organizers' collective ambition is to celebrate not just the centenary of quantum mechanics, but also the science and applications that arose from it in the past century – and to explore how quantum physics might bring further change in the century to come.

In May, Ghana, the country that originally proposed that the UN proclaim 2025 the year of quantum science, is hosting an international conference on the topic in Kumasi. And in August, science historians will meet to celebrate the quantum century in Salvador de Bahia in Brazil.

This meeting will be the high point of a 20-year research programme that set out to re-examine the development of quantum theory. One major aim of that work, says historian Michel Janssen at the University of Minnesota in Minneapolis, was to establish the contributions of a collective of scientists, many of whom – particularly women – have not been recognized in the history of the field.

These "hidden figures" include Lucy Mensing, who was a member of the same group as Heisenberg and worked out some of the first applications of his quantum-mechanical theory, says Daniela Monaldi, a historian at York University in Toronto, Canada. One of the most notable events of the year will be the publication of a biographical volume of essays on 16 of them, *Women in the History of Quantum Physics*.

For all that it has already brought, the quantum revolution still has unfinished business. In the years in which researchers were laying the foundations of quantum mechanics, they also began to rebuild other branches of physics – such as the study of electromagnetism, and states of matter – from quantum foundations. They also looked

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to extend their theories to encompass objects that move at close to light speed, something that the original quantum theory did not. These efforts drastically expanded the scope of quantum science and led researchers to develop the standard model of particles and fields, a process that finally came together in the 1970s.

The standard model has been incredibly successful, culminating in the 2012 discovery of its linchpin elementary particle, the Higgs boson. But these extensions lie on less-solid theoretical ground than quantum mechanics does — and leave several phenomena unexplained, such as the nature of the 'dark matter' that seems to greatly outweigh conventional, visible matter in the wider cosmos. Moreover, one important phenomenon, gravity, still resists being quantized.

Other conceptual problems of quantum physics remain open. In particular, researchers struggle to understand what exactly happens when experiments 'collapse' the fuzzy probabilities of quantum objects into one precise measurement, a key step in creating the — still remorselessly classical — macroscopic world we live in. Over the past few decades, researchers have been developing ways to turn these quirks of quantum reality into useful technologies. The resulting applications in computing, ultra-secure communications and innovative scientific instruments are still in their nascent stages.

Quantum theory keeps on giving. This year is an opportunity to celebrate and to make the broader public aware of the role that quantum physics has in their lives — and to inspire future generations, whoever they are and wherever they are in the world, to contribute to another quantum century.

We need to talk about human genome editing

In a few decades, gene-editing technologies could reduce the likelihood of common human diseases. Societies must use this time to prepare for their arrival.

Scientists know about tens of thousands of DNA variants that are associated with human diseases. On their own, the vast majority of these variants have small effects. But taken together, the result can be substantial. The effects of modifying multiple variants at once, known as polygenic genome editing, is the subject of an analysis published this week in *Nature* (P. M. Visscher *et al. Nature* https://doi.org/10.1038/s41586-024-08300-4; 2025).

The study reveals that polygenic genome editing in human embryos could substantially reduce the likelihood of certain diseases occurring, but it raises concerns, not least the renewed threat of eugenics. There are other caveats too, the researchers report. *Nature* is publishing this work because it is important to start a conversation about what could happen if more-sophisticated gene-editing technologies become available, which could be the case within 30 years, the authors say. Societies need to consider relevant benefits and risks before that day comes.

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Peter Visscher, a statistician and geneticist at the University of Queensland, Australia, and his colleagues modelled the consequences of simultaneously editing specific variants linked to a number of diseases, including Alzheimer's disease, schizophrenia, type 2 diabetes, coronary artery disease and major depressive disorder (MDD).

Gene-editing tools currently in development, called multiplex technologies, are projected in the coming decades to enable rapid precision DNA editing at tens, or even hundreds, of locations. The researchers found that, in some cases, editing a single variant associated with a polygenic disease can have strong effects, and, with the exception of MDD, editing up to ten genes associated with a disease can reduce its lifetime prevalence by an order of magnitude.

This would be a huge achievement. However, the authors also include an extensive discussion of the study's limitations and challenges. The fear that polygenic gene editing could be used for eugenics looms large among them, and is, in part, why no country currently allows genome editing in a human embryo, even for single variants.

There are also significant technical caveats. The authors say that polygenic editing is unlikely to benefit the wider population in any realistic timeframe, because the technology is available only through *in vitro* fertilization. There are also not yet enough known causal variants for common diseases. Other limitations to the findings include the fact that many diseases are also caused by non-genetic factors, which are harder to model. Furthermore, a successful new treatment for one of the diseases is likely to reduce the need for human genome editing. There are also pleiotropic effects to consider: a gene variant that is a risk factor for one disease could offer protection against another. And then there's the risk that these technologies will widen inequality and social divisions, because the costs will probably be substantial. These issues need society-wide discussion.

The past few decades have shown that new technologies are being developed ahead of conversations on their ethics or social and environmental impacts. From the atomic bomb to artificial intelligence, discussions of risks, benefits, safety, regulation and transparency have had to play catch-up. As recently as 2018, biophysicist He Jiankui shocked the world by announcing that he'd created genetically edited babies. The mistake should not be repeated.

Although it will be some decades before human-gene-editing science and technologies can be applied with precision and at scale, they are on their way; this is not a hypothetical issue. The intervening time should be used wisely. Societies need to be ready, understand the upsides and the dangers, and know what to do when that time comes.