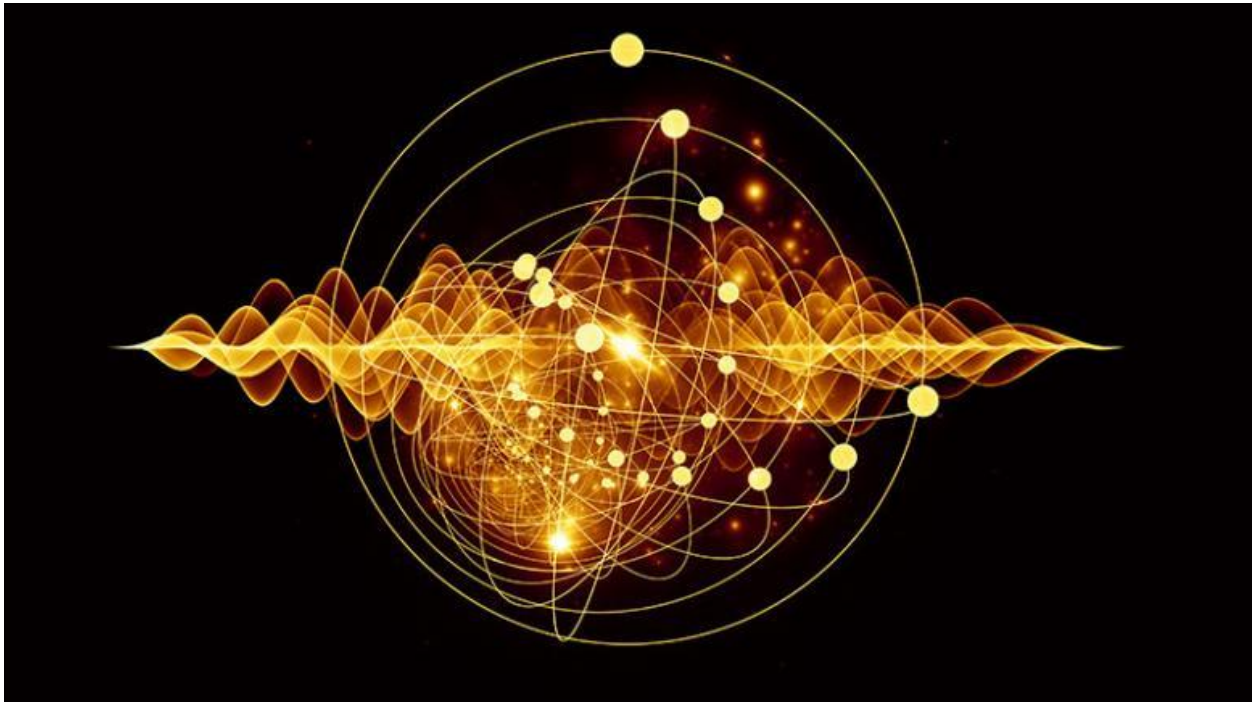


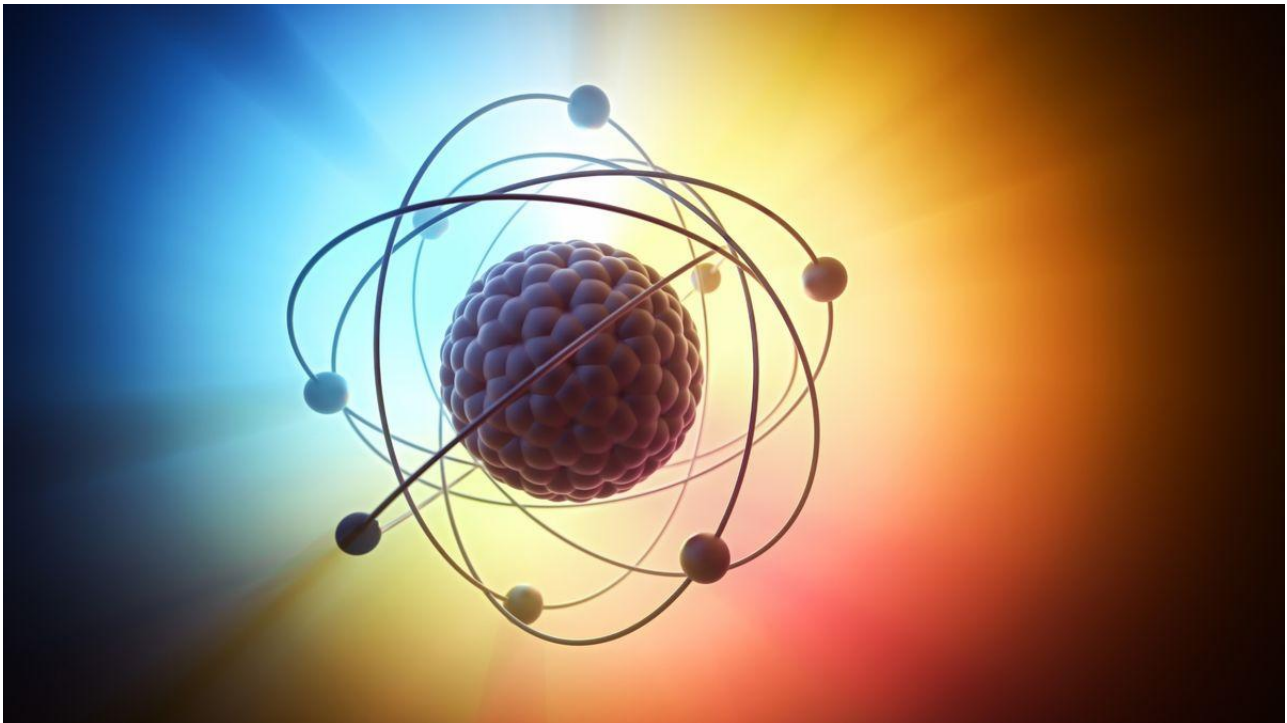
QUANTUM MECHANICS THEORY



Quantum mechanics: Definitions, axioms, and key concepts of quantum physics

last updated April 29, 2024

Quantum mechanics, or quantum physics, is the body of scientific laws that describe the wacky behavior of photons, electrons and the other subatomic particles that make up the universe.



Quantum physics describes the strange behavior of atoms and subatomic particles, sometimes leading to surprising and baffling results. (Image credit: Getty Images)

- [How is it different?](#)
 - [Who developed it?](#)
 - [Wave-particle duality](#)
 - [Describing atoms](#)
 - [Schrödinger's cat](#)
 - [Quantum entanglement](#)
 - [Quantum computing](#)
 - [Quantum mechanics and general relativity](#)
-

At the smallest scales, the universe behaves very differently than the everyday world we observe around us. Quantum mechanics is the subfield of physics that describes this bizarre behavior of microscopic particles — [atoms](#), electrons, photons and almost everything else in the molecular and submolecular realm.

Developed during the first half of the 20th century, the results of quantum mechanics are often extremely strange and counterintuitive. However, studying them has allowed physicists to reach a greater understanding about the nature of the universe, and could one day change the way we as humans process information.

HOW IS QUANTUM MECHANICS DIFFERENT FROM CLASSICAL PHYSICS?

At the scale of atoms and electrons, many of the equations of [classical mechanics](#), which describe the movement and interactions of things at everyday sizes and speeds, cease to be useful.

In classical mechanics, objects exist in a specific place at a specific [time](#). In quantum mechanics, objects instead exist in a haze of probability; they have a certain chance of being at point A, another chance of being at point B and so on.

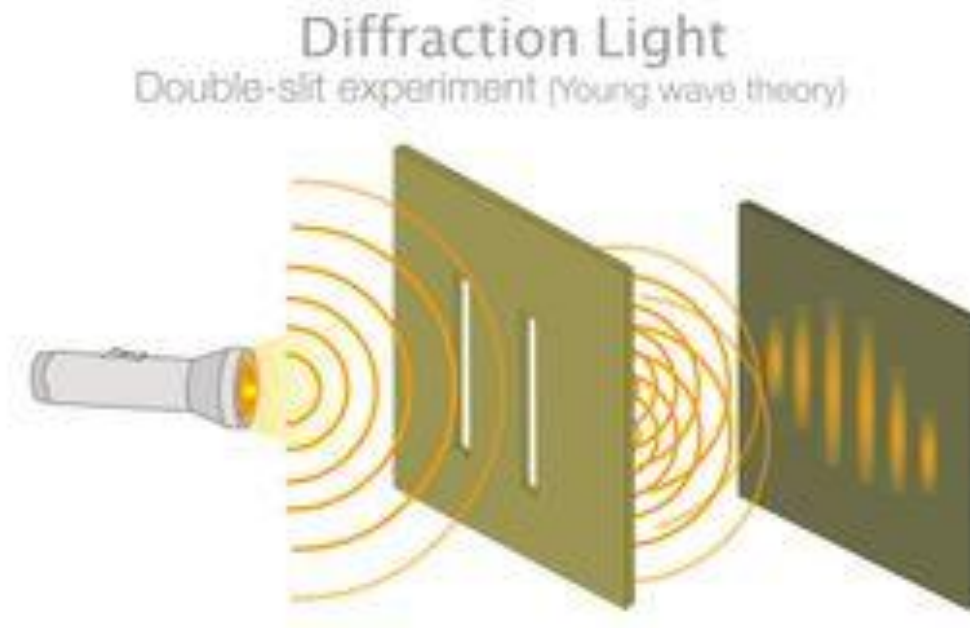
WHO DEVELOPED QUANTUM MECHANICS?

Unlike [Albert Einstein](#)'s famous [theory of relativity](#), which was developed at roughly the same time, the origins of quantum mechanics cannot be attributed to a single scientist. Rather, multiple scientists contributed to a foundation that gradually gained acceptance and experimental verification between the late 1800s and 1930, according to [the University of St. Andrews in Scotland](#). In 1900, German physicist Max Planck was trying to explain why objects at specific temperatures, like the 1,470-degree-Fahrenheit (800 degrees Celsius) filament of a light bulb, glowed a specific color — in this case, red, according to the [Perimeter Institute](#). Planck realized that equations used by physicist Ludwig Boltzmann to describe the behavior of gases could be translated into an explanation for this relationship between temperature and color. The problem was that Boltzmann's work relied on the fact that any given gas was made from tiny particles, meaning that light, too, was made from discrete bits.

This idea flew in the face of ideas about light at the time, when most physicists believed that light was a continuous wave and not a tiny packet. Planck himself didn't believe in either atoms or discrete bits of light, but his concept was given a boost in 1905, when Einstein published a paper, "[Concerning an Heuristic Point of View Toward the Emission and Transformation of Light](#)." Einstein envisioned light traveling not as a wave, but as some manner of "energy quanta." This packet of energy, Einstein suggested in his paper, could "be absorbed or generated only as a whole," specifically when an atom "jumps" between quantized vibration rates. This is where the "quantum" part of quantum mechanics comes from.

With this new way to conceive of light, Einstein offered insights into the behavior of nine phenomena in his paper, including the specific colors that Planck described being emitted from a light bulb filament. It also explained how certain colors of light could eject electrons off metal surfaces — a phenomenon known as the [photoelectric effect](#).

WHAT IS WAVE-PARTICLE DUALITY?



Here is a diagram of the double-slit experiment where electrons produce a wave pattern when two slits are used. (Image credit: grayjay via Shutterstock)

In quantum mechanics, particles can sometimes exist as waves and sometimes exist as particles. This can be most famously seen in the double-slit

experiment, where particles such as electrons are shot at a board with two slits cut into it, behind which sits a screen that lights up when an electron hits it. If the electrons were particles, they would create two bright lines where they had impacted the screen after passing through one or the other of the slits, according to a [popular article in Nature](#).

Instead, when the experiment is conducted, an interference pattern forms on the screen. This pattern of dark and bright bands makes sense only if the electrons are waves, with crests (high points) and troughs (low points), that can interfere with one another. Even when a single electron is shot through the slits at a time, the interference pattern shows up — an effect akin to a single electron interfering with itself.

In 1924, French physicist Louis de Broglie used the equations of Einstein's [theory of special relativity](#) to show that particles can exhibit wave-like characteristics and that waves can exhibit particle-like characteristics — a finding for which [he won the Nobel Prize a few years later](#).

HOW DOES QUANTUM MECHANICS DESCRIBE ATOMS?

In the 1910s, Danish physicist Niels Bohr tried to describe the internal structure of atoms using quantum mechanics. By this point, it was known that an atom was made of a heavy, dense, positively charged nucleus surrounded by a swarm of tiny, light, negatively charged electrons. Bohr put the electrons into orbits around the nucleus, like [planets](#) in a subatomic [solar system](#), except they could only have certain predefined orbital distances. By jumping from one orbit to another, the atom could receive or emit radiation at specific energies, reflecting their quantum nature.

Shortly afterward, two scientists, working independently and using separate lines of mathematical thinking, created a more complete quantum picture of the atom, according to [the American Physical Society](#). In Germany, physicist Werner Heisenberg accomplished this by developing "matrix mechanics." Austrian-Irish physicist Erwin Schrödinger developed a similar theory called "wave mechanics." Schrödinger showed in 1926 that these two approaches were equivalent.

The Heisenberg-Schrödinger model of the atom, in which each electron acts as a wave around the nucleus of an atom, replaced the earlier Bohr model. In the Heisenberg-Schrödinger model of the atom, electrons obey a "wave function"

and occupy "orbitals" rather than orbits. Unlike the circular orbits of the Bohr model, atomic orbitals have a variety of shapes, ranging from spheres to dumbbells to daisies, according to [an explanatory website from chemist Jim Clark](#).

WHAT IS THE SCHRÖDINGER'S CAT PARADOX?

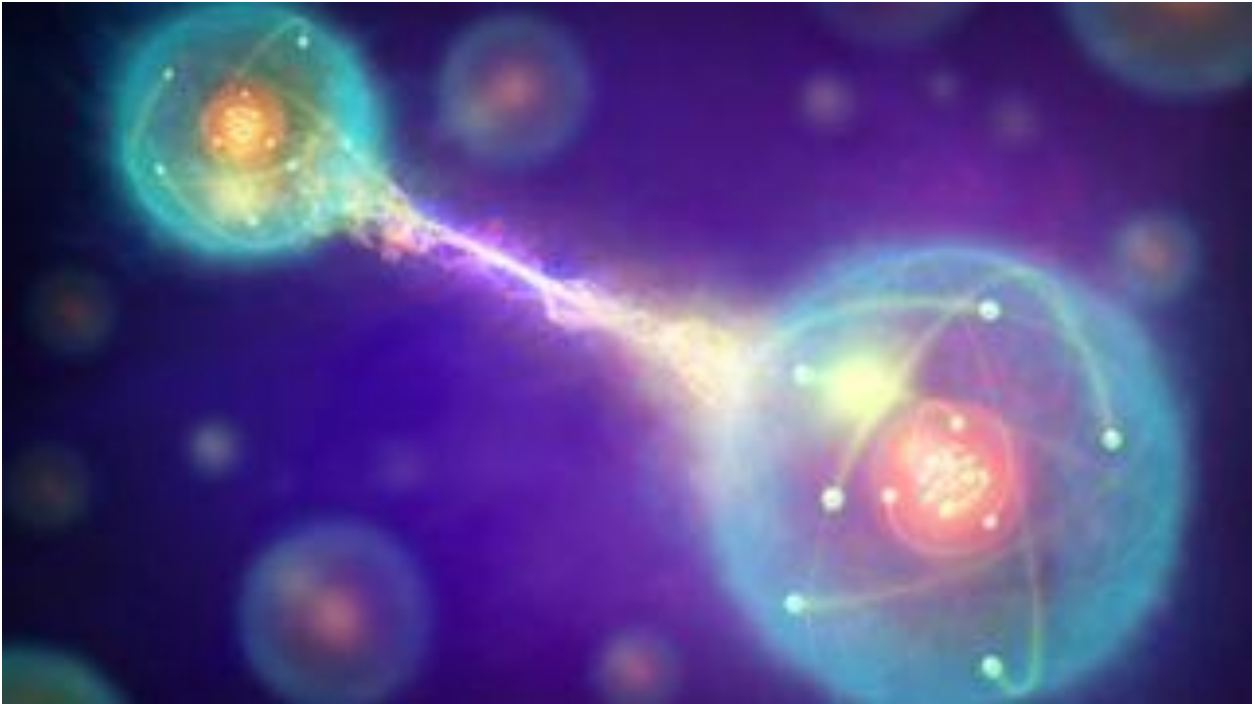
[Schrödinger's cat](#) is an often-misunderstood thought experiment describing the qualms that some of the early developers of quantum mechanics had with its results. While Bohr and many of his students believed that quantum mechanics suggested that particles don't have well-defined properties until they are observed, Schrödinger and Einstein were unable to believe such a possibility because it would lead to ridiculous conclusions about the nature of reality.

In 1935, Schrödinger proposed an experiment in which the life or death of a cat would depend on the random flip of a quantum particle, whose state would remain unseen until a box was opened. Schrödinger hoped to show the absurdity of Bohr's ideas with a real-world example that depended on the probabilistic nature of a quantum particle but yielded a nonsensical result.

According to Bohr's interpretation of quantum mechanics, until the box was opened, the cat existed in the impossible dual position of being both alive and dead at the same time. (No actual cat has ever been subjected to this experiment.) Both Schrödinger and Einstein believed that this helped show that [quantum mechanics was an incomplete theory](#) and would eventually be superseded by one that accorded with ordinary experience.

Even today, physicists struggle to explain why subatomic particles can seemingly exist in a superposition of different states, but large structures — like the universe itself — seemingly do not. [Proposed tweaks to Schrödinger's equations](#) could help resolve this tension, but so far none have been widely accepted by the scientific community.

WHAT IS QUANTUM ENTANGLEMENT?



Conceptual artwork of a pair of entangled quantum particles or events (left and right) interacting at a distance. Quantum entanglement is one of the consequences of quantum theory. Two particles will appear to be linked across space and time, with changes to one of the particles (such as an observation or measurement) affecting the other one. This instantaneous effect appears to be independent of both space and time, meaning that, in the quantum realm, effect may precede cause. (Image credit: MARK GARLICK/SCIENCE PHOTO LIBRARY via Getty Images)

Schrödinger and Einstein helped highlight another strange result of quantum mechanics that neither could fully fathom. In 1935, Einstein, along with physicists Boris Podolsky and Nathan Rosen, showed that two quantum particles can be set up so that their quantum states would always be correlated with one another, according to [the Stanford Encyclopedia of Philosophy](#). The particles essentially always "knew" about each other's properties. That means that measuring the state of one particle would instantaneously tell you the state of its twin, no matter how far apart they were, a result that Einstein called "spooky action at a distance," but which Schrödinger soon dubbed "[entanglement](#)."

Entanglement has been shown to be one of the most essential aspects of quantum mechanics and [occurs in the real world all the time](#). Researchers frequently conduct experiments using quantum entanglement and the phenomenon is part of the basis for the emerging field of [quantum computing](#).

WHAT IS QUANTUM COMPUTING?



A photo of a gold quantum computer. (Image credit: John D/Getty)

Unlike classical computers that process data using binary bits, which can be in one of two states — 0 or 1 — quantum computers use particles such as electrons or photons. These quantum bits, or qubits, represent a superposition of both 0 and 1 — meaning they can exist in multiple states at once.

This superposition enables quantum computers to perform calculations in parallel by processing all states of a qubit at the same time. Furthermore, quantum entanglement allows multiple qubits to share information and interact simultaneously, regardless of the distance between particles.

While quantum superposition and entanglement make the processing potential of quantum computers much higher than classical computers, the field has a long way to go. Currently, quantum computers are too small, too difficult to maintain and too error-prone to compete with the best classical computers. However, many experts expect this will one day change as the field advances.

ARE QUANTUM MECHANICS AND GENERAL RELATIVITY INCOMPATIBLE?



An image of an 'Einstein ring' captured by the Hubble Space Telescope. This cosmic phenomenon occurs when the massive gravity of a foreground object bends the light of a background object, just as Albert Einstein predicted. (Image credit: ESA/Hubble & NASA; Acknowledgment: Judy Schmidt)

At the moment, physicists lack a full explanation for all observed particles and forces in the universe, which is often called a theory of everything. Einstein's relativity describes large and massive things, while quantum mechanics describes small and insubstantial things. The two theories are not exactly incompatible, but nobody knows how to make them fit together.

Many researchers have sought a theory of quantum gravity, which would introduce gravity into quantum mechanics and explain everything from the subatomic to the supergalactic realms. There are a great deal of proposals for how to do this, such as inventing a hypothetical quantum particle for gravity called the graviton, but so far, no single theory has been able to fit all observations of objects in our universe. Another popular proposal, string theory, which posits that the most fundamental entities are tiny strings vibrating in many dimensions, has started to become less widely accepted by physicists since little evidence in its favor has been discovered. Other researchers have also worked on theories involving [loop quantum gravity](#), in

which both time and space come in discrete, tiny chunks, but so far no one idea has managed to gain a major hold among the physics community. *This article was originally written by Live Science contributor Robert Coolman and was updated by Adam Mann on March 2, 2022. It was updated again by Brandon Specktor on April 29, 2024.*

BIBLIOGRAPHY

- Bow, E. (2019, June 19). *A quick quantum history of the light bulb*. Inside the Perimeter <https://insidetheperimeter.ca/quick-quantum-history-of-the-light-bulb/>
- Clark, J. (2021, May). *Atomic orbitals*. <https://www.chemguide.co.uk/atoms/properties/atomorbs.html>
- Coolman, R. (2014, September 11). *What is classical mechanics?* Live Science. <https://www.livescience.com/47814-classical-mechanics.html>
- O'Connor, J. J., & Robertson, E. F. (1996, May). *A history of quantum mechanics*. https://mathshistory.st-andrews.ac.uk/HistTopics/The_Quantum_age_begins/
- Einstein, A. (1905). *On a heuristic point of view concerning the production and transformation of light*. Annals of Physics. <https://einsteinpapers.press.princeton.edu/vol2-trans/100>
- Mann, A. (2020, February 28) *Schrodinger's cat: The favorite misunderstood pet of quantum mechanics*. Live Science. <https://www.livescience.com/schrodingers-cat.html>
- Mann, A. (2019, August 29) *What is the theory of everything?* Space.com. <https://www.space.com/theory-of-everything-definition.html>
- Moskowitz, C. (2012, March 25). *Largest molecules yet behave like waves in quantum double-slit experiment*. Live Science. <https://www.livescience.com/19268-quantum-double-slit-experiment-largest-molecules.html>
- Schirber, M. (2019, July 9). *What is relativity?* Live Science. <https://www.livescience.com/32216-what-is-relativity.html>
- The Nobel Prize (n.d.). Louis de Broglie facts. <https://www.nobelprize.org/prizes/physics/1929/broglie/facts/>
- Tretkoff, E. (2008, February). *This month in physics history: February 1927 Heisenberg's uncertainty principle*. American Physical Society. <https://www.aps.org/publications/apsnews/200802/physicshistory.cfm>
- Wood, C. (2019, August 27). *What is quantum gravity?* Space.com. <https://www.space.com/quantum-gravity.html>

Google's Quantum Chip Sparks Debate on Multiverse Theory

December 16, 2024



Insider Brief

- Google's quantum chip *Willow* solved a computational problem in under five minutes, sparking debates about its implications for the multiverse theory.
- Hartmut Neven suggested the chip's performance aligns with the multiverse interpretation of quantum mechanics, but critics argue alternative explanations suffice.
- The task, Random Circuit Sampling, showcases quantum hardware's power but lacks direct evidence proving parallel universes.

Google's latest quantum computer chip, which the team dubbed *Willow*, has ignited a heated debate in the scientific community over the existence of parallel universes.

Following an eye-opening achievement in computational problem-solving, claims have surfaced that the chip's success aligns with the theory of a multiverse, a concept that suggests our universe is one of many coexisting in parallel dimensions. In this piece, we'll examine both sides of this argument that seems to have opened up a parallel universe of its own — with one universe of scientists suggesting the Willow experiments offer evidence of a multiverse and the other suggesting it has nothing to do with the theory at all.

10 SEPTILLION YEARS IS A LONG TIME FOR A UNIVERSE

According to Google, *Willow* solved a computational problem in under five minutes — [a task that would have taken the world's fastest supercomputers approximately 10 septillion years](#). This staggering feat, announced in [a blog post](#) and accompanied by a study in the journal [Nature](#), demonstrates the extraordinary potential of quantum computing to tackle problems once thought unsolvable within a human timeframe.

[Google Quantum AI](#) team founder Hartmut Neven argued that the chip's success supports [the idea of quantum computation occurring in many parallel universes](#), aligning with interpretations of quantum mechanics that are based on a multiverse.

Neven's comments echo the theories of [British physicist David Deutsch](#), who was among the first to suggest that quantum computation might involve parallel universes. Deutsch's multiverse interpretation of quantum mechanics proposes that particles exist in multiple states simultaneously, a phenomenon that quantum computers leverage for their computational power.

DAVID DEUTSCH'S MULTIVERSE THEORY AND ITS CONNECTION TO QUANTUM COMPUTING

Deutsch was one of the first scientists to explicitly connect quantum mechanics with the multiverse. His work, particularly in the 1980s, built on the "[many-worlds interpretation](#)" of quantum mechanics proposed by Hugh Everett in the 1950s.

The many-worlds interpretation attempts to show that every quantum event results in a branching of the universe into multiple, coexisting realities. For example, if a particle can exist in two states, the universe splits into two versions — one for each state. These branches are not merely hypothetical but are thought to represent real, parallel universes.

Deutsch extended this idea to quantum computing. In his view, when a quantum computer performs a computation, in broad strokes, it simultaneously processes information in multiple parallel universes. Each computation takes place in a distinct branch of reality, and the quantum computer effectively leverages this multiplicity to solve problems that are impossible for classical computers.

In practical terms, Deutsch argued that the extraordinary efficiency of quantum algorithms, such as Shor's algorithm for factoring large numbers, can only be fully understood if quantum computers are seen as working across parallel universes. This interpretation has been highly influential, though not (as we shall see) universally accepted. Still, the idea remains a cornerstone of the multiverse argument in quantum mechanics.

The claims surrounding Google's Willow chip resonate with Deutsch's theories, as the chip's computational feats appear to align with his description of quantum computing as an inherently multiverse-dependent process. However, skeptics caution that Deutsch's interpretation is one of many competing frameworks within quantum mechanics, and more experimental evidence is needed to validate or refute the multiverse hypothesis.

THE PROS AND CONS: DOES WILLOW PROVE THE MULTIVERSE?

So, let's take an objective look at both sides of the argument – and you can decide whether Willow has, besides performing a quick calculation, opened up parallel universes.

Ways Willow Supports the Multiverse Theory:

Quantum Computation's Dependence on Superposition

Willow's ability to perform calculations exponentially faster than classical computers relies on the phenomenon of superposition, where qubits exist –multiverse theorists would suggest – in multiple states simultaneously. In the multiverse interpretation, these states correspond to computations occurring across parallel universes, offering evidence that the multiverse is not just theoretical but operational within quantum systems.

Hartmut Neven's Assertion

The leader of Google's Quantum AI team explicitly linked Willow's success to the multiverse, suggesting that quantum computation's extraordinary power could be a direct result of interactions across parallel dimensions. This aligns with interpretations of quantum mechanics that posit the multiverse as essential for explaining such phenomena.

In [Neven's words](#): "This mind-boggling number exceeds known timescales in physics and vastly exceeds the age of the universe. It lends credence to the notion that quantum computation occurs in many parallel universes, in line with the idea that we live in a multiverse, a prediction first made by David Deutsch."

Historical Roots in Multiverse Interpretations

The achievement echoes David Deutsch's seminal work, which argues that the power of

quantum computing lies in the simultaneous computation of parallel universes. Willow may offer experimental evidence to support his hypothesis.

Ways Willow Doesn't Prove the Multiverse:

Alternative Interpretations of Quantum Mechanics:

Critics like Ethan Siegel argue that quantum phenomena, including superposition and entanglement, can be explained without invoking the multiverse. These interpretations, such as the Copenhagen or pilot-wave theories, suggest that Willow's success may arise from purely physical and mathematical principles within a single universe.

In Siegel's words: "Neven has conflated the notion of a quantum mechanical Hilbert space, which is an infinite-dimensional mathematical space where quantum mechanical wavefunctions 'live,' with the notion of parallel universes and a multiverse."

Impressive But Not Single Universe Impossible

Critics also suggest that the problem solved by Willow — Random Circuit Sampling — is primarily a benchmark problem, designed to demonstrate the unique capabilities of quantum hardware rather than address practical applications. They also suggests that, just as in the 2019 Sycamore feat, savvy computers scientists in the future may coax classical computers into performing Willow's feat without the reliance on parallel universes.

Lack of Direct Evidence:

While Willow demonstrates the potential of quantum systems, it does not provide empirical proof of parallel universes. Some scientists suggest that because the multiverse remains a theoretical construct, its existence cannot yet be confirmed through current experimental methods.

Speculative Linkages:

Associating Willow's computational breakthroughs with the multiverse might be more philosophical than scientific at this stage. The extraordinary speed of quantum computation can be celebrated without necessarily tying it to the existence of parallel dimensions.

WHAT DOES WILLOW REALLY PROVE?

Willow's achievement represents a significant leap forward in quantum computing, particularly in error reduction and problem-solving capacity. However, claims about proving the multiverse remain speculative. For now, the multiverse remains a tantalizing theory without concrete evidence.

Regardless of its implications for cosmology, one thing both universes of scientists seem to agree on is that Willow is a great example of the accelerating pace of quantum innovation and — while not all scientists agree on this — Willow’s performance even hints at transformative applications in fields such as cryptography, material science, and artificial intelligence. Maybe something that’s been drowned out by the debate is the debate, itself. Beyond the commercial applications, quantum computers are positioned to prompt scientific discussions and deeper investigations — and that’s a positive that’s often missed in the rhetoric around use cases.

Whether or not the chip validates the multiverse, well, at least in this universe, that’s up for continued debate.

What is Quantum Computing?

Quantum computing is an advanced form of computation that leverages the principles of quantum mechanics—such as superposition, entanglement, and quantum tunneling. Unlike classical computers, which process information in binary bits (0s and 1s), quantum computers use quantum bits, or qubits, which can represent and process multiple states simultaneously. This ability enables quantum computers to solve highly complex problems far faster than classical computers, unlocking opportunities in fields that require massive computational power.

Overcoming Current Limitations

While quantum computing holds immense promise, it faces significant hurdles. Current quantum systems are error-prone and require highly controlled environments, including extremely low temperatures, to function. Moreover, scaling up quantum computers for practical applications in genetics will require advancements in hardware stability and error correction. Despite these limitations, ongoing research and development suggest that these challenges may be overcome in the coming decades.

Copenhagen Interpretation of Quantum Mechanics

First published Fri May 3, 2002; substantive revision Fri May 31, 2024

As the theory of the atom, quantum mechanics is perhaps the most successful theory in the history of science. It enables physicists, chemists, and technicians to calculate and predict the outcome of a vast number of experiments and to create new and advanced technology based on the insight into the behavior of atomic objects. But it is also a theory that challenges our imagination. It seems to violate some fundamental principles of classical physics, principles that eventually have become a part of western common sense since the rise of the modern worldview in the Renaissance. The aim of any metaphysical interpretation of quantum mechanics is to account for these violations.

The Copenhagen interpretation was the first general attempt to understand the world of atoms as this is represented by quantum mechanics. The founding father was mainly the Danish physicist Niels Bohr, but also Werner Heisenberg, Max Born and other physicists made important contributions to the overall understanding of the atomic world that is associated with the name of the capital of Denmark.

In fact Bohr and Heisenberg never totally agreed on how to understand the mathematical formalism of quantum mechanics, and neither of them ever used the term “the Copenhagen interpretation” as a joint name for their ideas. In fact, Bohr once distanced himself from what he considered to be Heisenberg’s more subjective interpretation (*APHK*, p. 51). The term is rather a label introduced by people opposing Bohr’s idea of complementarity, to identify what they saw as the common features behind the Bohr-Heisenberg interpretation as it emerged in the late 1920s. Today the Copenhagen interpretation is mostly regarded as synonymous with indeterminism, Bohr’s correspondence principle, Born’s statistical interpretation of the wave function, and Bohr’s complementarity interpretation of certain atomic phenomena.

- [1. The Background](#)
- [2. Classical Physics](#)
- [3. The Correspondence Rule](#)
- [4. Complementarity](#)

- 5. The Use of Classical Concepts
 - 6. The Interpretation of the Quantum Formalism
 - 7. Misunderstandings of Complementarity
 - 8. The Divergent Views
 - 9. The Measurement Problem
 - 10. Complementarity, Decoherence, and Probabilities
 - 11. New Perspectives
 - Bibliography
-

1. The Background

In 1900 Max Planck discovered that the radiation spectrum of black bodies occurs only with discrete energies separated by the value $h\nu$, where ν is the frequency and h is a new constant, the so-called Planck constant. According to classical physics, the intensity of this continuous radiation would grow unlimitedly with growing frequencies, resulting in what was called the ultraviolet catastrophe. But Planck's suggestion was that if black bodies only exchange energy with the radiation field in a proportion equal to $h\nu$ that problem would disappear. The fact that the absorption and the emission of energy is discontinuous is in conflict with the principles of classical physics. A few years later Albert Einstein used this discovery in his explanation of the photoelectric effect. He suggested that light waves were quantized, and that the amount of energy which each quantum of light could deliver to the electrons of the cathode, was exactly $h\nu$. The next step came in 1911 when Ernest Rutherford performed some experiments shooting alpha particles into a gold foil. Based on these results he could set up a model of the atom in which the atom consisted of a heavy nucleus with a positive charge surrounded by negatively charged electrons like a small solar system. Also this model was in conflict with the laws of classical physics. According to classical mechanics and electrodynamics, one might expect that the electrons orbiting around a positively charged nucleus would continuously emit radiation so that the nucleus would quickly swallow the electrons.

At this point Niels Bohr entered the scene and soon became the leading physicist on atoms. In 1913 Bohr, visiting Rutherford in Manchester, put forward a mathematical model of the atom which provided the first theoretical support for

Rutherford's model and could explain the emission spectrum of the hydrogen atom (the Balmer series). The theory was based on two postulates:

1. An atomic system is only stable in a certain set of states, called stationary states, each state being associated with a discrete energy, and every change of energy corresponds to a complete transition from one state to another.
2. The possibility for the atom to absorb and emit radiation is determined by a law according to which the energy of the radiation is given by the energy difference between two stationary states being equal to $h\nu$.

Some features of Bohr's semi-classical model were indeed very strange compared to the principles of classical physics. It introduced an element of discontinuity and indeterminism foreign to classical mechanics:

1. Apparently not every point in space was accessible to an electron moving around a hydrogen nucleus. An electron moved in classical orbits, but during its transition from one orbit to another it was at no definite place between these orbits. Thus, an electron could only be in its ground state (the orbit of lowest energy) or an excited state (if an impact of another particle had forced it to leave its ground state.)
2. It was impossible to predict when the transition would take place and how it would take place. Moreover, there were no external (or internal) causes that determined the "jump" back again. Any excited electron might in principle move spontaneously to either a lower state or down to the ground state.
3. Rutherford pointed out that if, as Bohr did, one postulates that the frequency of light ν , which an electron emits in a transition, depends on the difference between the initial energy level and the final energy level, it appears as if the electron must "know" to what final energy level it is heading in order to emit light with the right frequency.
4. Einstein made another strange observation. He was curious to know in which direction the photon decided to move off from the electron.

Between 1913 and 1925 Bohr, Arnold Sommerfeld and others were able to improve Bohr's model, and together with the introduction of spin and Wolfgang Pauli's exclusion principle it gave a reasonably good description of the basic chemical elements. The model ran into problems, nonetheless, when one tried to apply it to spectra other than that of hydrogen. So there was a general feeling among all leading physicists that Bohr's model had to be replaced by a more radical theory. In 1925 Werner Heisenberg, at that time Bohr's assistant in Copenhagen, laid down the basic principles of a complete quantum mechanics. In

his new matrix theory he replaced classical commuting variables with non-commuting ones. The following year, Erwin Schrödinger gave a simpler formulation of the theory in which he introduced a second-order differential equation for a wave function. He himself attempted a largely classical interpretation of the wave function. However, already the same year Max Born proposed a consistent statistical interpretation in which the square of the absolute value of this wave function expresses a probability density for the outcome of a measurement.

2. Classical Physics

Bohr saw quantum mechanics as a generalization of classical physics although it violates some of the basic ontological principles on which classical physics rests. Some of these principles are:

- *The principles of physical objects and their identity:*
 - Physical objects (systems of objects) exist in space and time and physical processes take place in space and time, i.e., it is a fundamental feature of all changes and movements of physical objects (systems of objects) that they happen on a background of space and time;
 - Physical objects (systems) are localizable, i.e., they do not exist everywhere in space and time; rather, they are confined to definite places and times;
 - A particular place can only be occupied by one object of the same kind at a time;
 - Two physical objects of the same kind exist separately; i.e., two objects that belong to the same kind cannot have identical location at an identical time and must therefore be separated in space and time;
 - Physical objects are countable, i.e., two alluded objects of the same kind count numerically as one if both share identical location at a time and counts numerically as two if they occupy different locations at a time;
- *The principle of separated properties*, i.e., two objects (systems) separated in space and time have each independent inherent states or properties;

- *The principle of value determinateness*, i.e., all inherent states or properties have a specific value or magnitude independent of the value or magnitude of other properties;
- *The principle of causality*, i.e., every event, every change of a system, has a cause;
- *The principle of determination*, i.e., every later state of a system is uniquely determined by any earlier state;
- *The principle of continuity*, i.e., all processes exhibiting a difference between the initial and the final state have to go through every possible intervening state; in other words, the evolution of a system is an unbroken path through its state space; and finally
- *The principle of the conservation of energy*, i.e., the energy of a closed system can be transformed into various forms but is never gained, lost or destroyed.

Due to these principles it is possible within, say, classical mechanics, to define a state of a system at any later time with respect to a state at any earlier time. So whenever we know the initial state consisting of the system's position and momentum, and know all external forces acting on it, we also know what will be its later states. The knowledge of the initial state is usually acquired by observing the state properties of the system at the time selected as the initial moment. Furthermore, the observation of a system does not affect its later behavior or, if observation somehow should influence this behavior, it is always possible to incorporate the effect into the prediction of the system's later state. Thus, in classical physics we can always draw a sharp distinction between the state of the measuring instrument being used on a system and the state of the physical system itself. It means that the physical description of the system is objective because the definition of any later state is not dependent on measuring conditions or other observational conditions.

Much of Kant's philosophy can be seen as an attempt to provide satisfactory philosophical grounds for the objective basis of Newton's mechanics against Humean scepticism. Kant thus argued that classical mechanics is in accordance with the transcendental conditions for objective knowledge. Kant's philosophy undoubtedly influenced Bohr in various ways, as many scholars in recent years have noticed (Hooker 1972; Folse 1985; Honner 1987; Faye 1991; Kaiser 1992; and Chevalley 1994). Bohr was definitely neither a subjectivist nor a positivist philosopher, as Karl Popper (1967) and Mario Bunge (1967) have claimed. He explicitly rejected the idea that the experimental outcome is due to the observer. As

he said: “It is certainly not possible for the observer to influence the events which may appear under the conditions he has arranged” (*APHK*, p. 51). Not unlike Kant, Bohr thought that we could have objective knowledge only in case we can distinguish between the experiential subject and the experienced object. It is a precondition for the knowledge of a phenomenon as being something distinct from the sensorial subject, that we can refer to it as an object without involving the subject’s experience of the object. In order to separate the object from the subject itself, the experiential subject must be able to distinguish between the form and the content of his or her experiences. This is possible only if the subject uses causal and spatial-temporal concepts for describing the sensorial content, placing phenomena in causal connection in space and time, since it is the causal space-time description of our perceptions that constitutes the criterion of reality for them. Bohr therefore believed that what gives us the possibility of talking about an object and an objectively existing reality is the application of those necessary concepts, and that the physical equivalents of “space,” “time,” “causation,” and “continuity” were the concepts “position,” “time,” “momentum,” and “energy,” which he referred to as *the classical concepts*. He also believed that the above basic concepts exist already as preconditions of unambiguous and meaningful communication, built in as rules of our ordinary language. So, in Bohr’s opinion the conditions for an objective description of nature given by the concepts of classical physics were merely a refinement of the preconditions of human knowledge.

3. The Correspondence Rule

The guiding principle behind Bohr’s and later Heisenberg’s work in the development of a consistent theory of atoms was the correspondence rule. The full rule states that a transition between stationary states is allowed if, and only if, there is a corresponding harmonic component in the classical motion (*CW Vol. 3*, p. 479). Bohr furthermore realized that according to his theory of the hydrogen atom, the frequencies of radiation due to the electron’s transition between stationary states with high quantum numbers, i.e. states far from the ground state, coincide approximately with the results of classical electrodynamics. Hence in the search for a theory of quantum mechanics it became a methodological requirement to Bohr that any further theory of the atom should predict values in domains of high quantum numbers that should be a close approximation to the values of classical physics. The correspondence rule was a heuristic principle meant to make sure that in areas where the influence of Planck’s constant could be neglected the numerical values predicted by such a theory should be the same as if they were predicted by classical radiation theory.

The Bohr-Sommerfeld core model of the atomic structure came into trouble in the beginning of the 1920s due to the fact that it couldn't handle an increasing number of spectroscopic phenomena. In 1924 Wolfgang Pauli introduced a new degree of freedom according to which two electrons with the same known quantum numbers could not be in the same state. A year later, in 1925, Ralph Kronig, Georg Uhlenbeck and Samuel Goudsmit explained this new degree of freedom by introducing the non-classical concept of electron spin. It has been suggested, however, that Pauli's proposal meant a lethal blow not only to the Bohr-Sommerfeld model, but also to the correspondence principle because "how to reconcile the classical periodic motions presupposed by the correspondence principle with the classically non-describable *Zweideutigkeit* of the electron's angular momentum?" (Massimi 2005, p. 73)

Although the exclusion rule and the introduction of spin broke with the attempt to explain the structure of the basic elements along the lines of the correspondence argument (as Pauli pointed out in a letter to Bohr) Bohr continued to think of it as an important methodological principle in the attempt to establish a coherent quantum theory. In fact, he repeatedly expressed the opinion that Heisenberg's matrix mechanics came to light under the guidance of this very principle. In his Faraday Lectures from 1932, for instance, Bohr emphasizes: "A fundamental step towards the establishing of a proper quantum mechanics was taken in 1925 by Heisenberg who showed how to replace the ordinary kinematical concepts, in the spirit of the correspondence argument, by symbols referring to the elementary processes and the probability of their occurrence" (CC, p. 48). Bohr acknowledged, however, that the correspondence argument failed too in those cases where particular non-classical concepts have to be introduced into the description of atoms. But he still thought that the correspondence argument was indispensable for both structural and semantic reasons in constructing a proper quantum theory as a generalised theory from classical mechanics.

Indeed, spin is a quantum property of the electrons which cannot be understood as a classical angular momentum. Needless to say, Bohr fully understood that. But he didn't think that this discovery ruled out the use of the correspondence rule as guidance to finding a satisfactory quantum theory. A lengthy quotation from Bohr's paper "The Causality Problem in Atomic Physics" (1938) gives evidence for this:

Indeed, as adequate as the quantum postulates are in the phenomenological description of the atomic reactions, as indispensable are the basic concepts of mechanics and electrodynamics for the specification of atomic structures and for the definition of fundamental properties of the agencies with which they react. Far

from being a temporary compromise in this dilemma, the recourse to essentially statistical considerations is our only conceivable means of arriving at a generalization of the customary way of description sufficiently wide to account for the features of individuality expressed by the quantum postulates and reducing to classical theory in the limiting case where all actions involved in the analysis of the phenomena are large compared with a single quantum. In the search for the formulation of such a generalization, our only guide has just been the so called correspondence argument, which gives expression for the exigency of upholding the use of classical concepts to the largest possible extent compatible with the quantum postulates. (CC, p. 96)

This shows that, according to Bohr, quantum mechanics, as formulated by Heisenberg, was a rational generalization of classical mechanics when the quantum of action and the spin property were taken into account.

The correspondence rule was an important methodological principle. In the beginning it had mostly a clear technical meaning for Bohr as a principle of theory construction, but later he also recognized it as having a specific interpretative function. Apparently, Bohr's use of the principle up to Heisenberg's formulation of quantum mechanics was as a heuristic principle for how to generalize mathematically a coherent theory from classical mechanics, while afterwards he relied on it to support his understanding of the physical meaning of the new theory. In the first situation, the pre-QM, Bohr used the principle dynamically as a methodological principle for generating a new theory (Bokulich & Bokulich 2005). As a methodological principle, it guided physicists to how a coherent theory of quantum phenomena might be achieved, and as a methodological principle, it can be understood as an umbrella principle that applied to different aspects of a formal (syntactical) extension of classical physics depending on the context of discussion. In the second situation, post-QM, his appeal to the correspondence principle had more the character of a vindication of his own interpretation of quantum mechanics. In this post-QM situation, the principle achieved a semantic role in the sense that Bohr saw it as a consequence of the descriptive demand of using classical concepts, and thereby his physical interpretation of the QM formalism in relation to the theory's description of experimental results.

It is obvious that it makes no sense to compare the numerical values of the theory of atoms with those of classical physics unless the meaning of the physical terms in both theories is commensurable. The correspondence rule was based on the epistemological idea that classical concepts were indispensable for our understanding of physical reality, and it is only when classical phenomena and quantum phenomena are described in terms of the same classical concepts that we

can compare different physical experiences. It was this broader sense of the correspondence rule that Bohr often had in mind later on. He directly mentioned the relationship between the use of classical concepts and the correspondence principle in 1934 when he wrote in the Introduction to *Atomic Theory and the Description of Nature*:

[T]he necessity of making an extensive use ... of the classical concepts, upon which depends ultimately the interpretation of all experience, gave rise to the formulation of the so-called correspondence principle which expresses our endeavours to utilize all the classical concepts by giving them a suitable quantum-theoretical re-interpretation. (*ATDN*, p. 8)

Bohr's practical methodology stands therefore in direct opposition to Thomas Kuhn and Paul Feyerabend's historical view that succeeding theories, like classical mechanics and quantum mechanics, are incommensurable. In contrast to their philosophical claims of meaning gaps and partial lack of rationality in the choice between incommensurable theories, Bohr believed not just retrospectively that quantum mechanics was a natural generalization of classical physics, but he and Heisenberg followed in practice the requirements of the correspondence rule. Thus, in the mind of Bohr, the meaning of the classical concepts did not change but their application was restricted. This was the lesson of complementarity.

4. Complementarity

After Heisenberg had managed to formulate a consistent quantum mechanics in 1925, both he and Bohr began their struggle to find a coherent interpretation for the mathematical formalism. Heisenberg and Bohr followed somewhat different approaches (Camilleri 2009). Where Heisenberg looked to the formalism and developed his famous uncertainty principle or indeterminacy relation, Bohr chose to analyze concrete experimental arrangements, especially the double-slit experiment. In a way Bohr merely regarded Heisenberg's relation as an expression of his general notion that our understanding of atomic phenomena builds on complementary descriptions. At Como in 1927 he presented for the first time his ideas according to which certain different descriptions are said to be complementary. Bohr never gave a precise definition of complementarity; however, Simon Saunders (2005) offers a formal reconstruction of complementarity in modern terminology.

Bohr pointed to two sets of descriptions which he took to be complementary. On the one hand, there are those that attribute either kinematic or dynamic properties to the atom; that is, "space-time descriptions" are complementary to "claims of causality", where Bohr interpreted the causal claims in physics in terms of the

conservation of energy and momentum. On the other hand, there are those descriptions that ascribe either wave or particle properties to a single object. How these two kinds of complementary sets of descriptions are related is something Bohr never indicated (Murdoch 1987). Even among people, like Rosenfeld and Pais, who claimed to speak on behalf of Bohr, there is no agreement. The fact is that the description of light as either particles or waves was already a classical dilemma, which not even Einstein's definition of a photon really solved since the momentum of the photon as a particle depends on the frequency of the light as a wave. Furthermore, Bohr eventually realized that the attribution of kinematic and dynamic properties to an object is complementary because the ascription of both of these conjugate variables rests on mutually exclusive experiments. The attribution of particle and wave properties to an object may, however, occur in a single experiment; for instance, in the double-slit experiment where the interference pattern consists of single dots. So within less than ten years after his Como lecture Bohr tacitly abandoned "wave-particle complementarity" in favor of the exclusivity of "kinematic-dynamic complementarity" (Held 1994).

It was clear to Bohr that any interpretation of the atomic world had to take into account an important empirical fact. The discovery of the quantization of action meant that quantum mechanics could not fulfill the above principles of classical physics. Every time we measure, say, an electron's position, the apparatus and the electron interact in an uncontrollable way, so that we are unable to measure the electron's momentum at the same time. Until the mid-1930s when Einstein, Podolsky and Rosen published their famous thought-experiment with the intention of showing that quantum mechanics was incomplete, Bohr spoke as if the measurement apparatus disturbed the electron. This paper had a significant influence on Bohr's line of thought. Apparently, Bohr realized that speaking of disturbance seemed to indicate—as some of his opponents may have understood him—that atomic objects were classical particles with definite inherent kinematic and dynamic properties. After the EPR paper he stated quite clearly: "the whole situation in atomic physics deprives of all meaning such inherent attributes as the idealization of classical physics would ascribe to such objects."

Hence, according to Bohr, the state of the measuring device and the state of the object cannot be separated from each other during a measurement but they form a dynamical whole. Bohr called this form of holism "the individuality" of the atomic process. Thereby, he had in mind not only that the interaction is uncontrollable but also that the system-cum-measurement forms an inseparable unity due to the entanglement – although Bohr's did not use this term (Faye 1991, 1994; Howard 1994, 2004).

Also after the EPR paper Bohr spoke about Heisenberg's "indeterminacy relation" as indicating the ontological consequences of his claim that kinematic and dynamic variables are ill-defined unless they refer to an experimental outcome. Earlier he had often called it Heisenberg's "uncertainty relation", as if it were a question of a merely epistemological limitation. Furthermore, Bohr no longer mentioned descriptions as being complementary, but rather phenomena or information. He introduced the definition of a "phenomenon" as requiring a complete description of the entire experimental arrangement, and he took a phenomenon to be a measurement of the values of either kinematic or dynamic properties.

Bohr's more mature view, i.e., his view after the EPR paper, on complementarity and the interpretation of quantum mechanics may be summarized in the following points:

1. The interpretation of a physical theory has to rely on an experimental practice.
2. The experimental practice presupposes a certain pre-scientific practice of description, which establishes the norm for experimental measurement apparatus, and consequently what counts as scientific experience.
3. Our pre-scientific practice of understanding our environment is an adaptation to the sense experience of separation, orientation, identification and reidentification over time of physical objects.
4. This pre-scientific experience is grasped in terms of common categories like thing's position and change of position, duration and change of duration, and the relation of cause and effect, terms and principles that are now parts of our common language.
5. These common categories yield the preconditions for objective knowledge, and any description of nature has to use these concepts to be objective.
6. The concepts of classical physics are merely exact specifications of the above categories.
7. The classical concepts—and not classical physics itself—are therefore necessary in any description of physical experience in order to understand what we are doing and to be able to communicate our results to others, in particular in the description of quantum phenomena as they present themselves in experiments;
8. Planck's empirical discovery of the quantization of action requires a revision of the foundation for the use of classical concepts, because they are not all applicable at the same time. Their use is well defined only if they apply to

experimental interactions in which the quantization of action can be regarded as negligible.

9. In experimental cases where the quantization of action plays a significant role, the application of a classical concept does not refer to independent properties of the object; rather the ascription of either kinematic or dynamic properties to the object as it exists independently of a specific experimental interaction is ill-defined.
10. The quantization of action demands a limitation of the use of classical concepts so that these concepts apply only to a phenomenon, which Bohr understood as the macroscopic manifestation of a measurement on the object, i.e. the uncontrollable interaction between the object and the apparatus.
11. The quantum mechanical description of the object differs from the classical description of the measuring apparatus, and this requires that the object and the measuring device should be separated in the description, but the line of separation is not the one between macroscopic instruments and microscopic objects. It has been argued in detail (Howard 1994) that Bohr pointed out that parts of the measuring device may sometimes be treated as parts of the object in the quantum mechanical description.
12. The quantum mechanical formalism does not provide physicists with a 'pictorial' representation: the ψ -function does not, as Schrödinger had hoped, represent a new kind of reality. Instead, as Born suggested, the square of the absolute value of the ψ -function expresses a probability density for the outcome of a measurement. Due to the fact that the wave equation involves an imaginary quantity this equation can have only a symbolic character, but the formalism may be used to predict the outcome of a measurement that establishes the conditions under which concepts like position, momentum, time and energy apply to the phenomena.
13. The ascription of these classical concepts to the phenomena of measurements rely on the experimental context of the phenomena, so that the entire setup provides us with the defining conditions for the application of kinematic and dynamic concepts in the domain of quantum physics.
14. Such phenomena are complementary in the sense that their manifestations depend on mutually exclusive measurements, but that the information gained through these various experiments exhausts all possible objective knowledge of the object.

Bohr thought of the atom as real. Atoms are neither heuristic nor logical constructions. A couple of times he emphasized this directly using arguments from

experiments in a very similar way to Ian Hacking and Nancy Cartwright much later. What he did not believe was that the quantum mechanical formalism was true in the sense that it gave us a literal ('pictorial') rather than a symbolic representation of the quantum world. It makes much sense to characterize Bohr in modern terms as an entity realist who opposes theory realism (Folse 1986; Faye 1991).

It is because of the imaginary quantities in quantum mechanics (where the commutation rule for canonically conjugate variable, p and q , introduces Planck's constant into the formalism by $qp - pq = i\hbar/2\pi$ that quantum mechanics does not give us a 'pictorial' representation of the world. Neither does the theory of relativity, Bohr argued, provide us with a literal representation, since the velocity of light is introduced with a factor of i in the definition of the fourth coordinate in a four-dimensional manifold (CC, p. 86 and p. 105). Instead these theories can only be used symbolically to predict observations under well-defined conditions. Therefore, many philosophers have interpreted Bohr as an antirealist or an instrumentalist when it comes to theories. However, Bohr's reference to the use of imaginary number in quantum mechanics as an argument for his rejection of a pictorial representation may seem misplaced. The use of imaginary numbers is more a question about the conventional choice of scale whether measurements should be represented in terms of imaginary or real number than an indication of a certain magnitude expressed in terms of these numbers is not real. Dieks (2017) gives a nuanced discussion of Bohr's argument, and he concludes that in the context of quantum mechanics Bohr saw imaginary numbers to be associated with incompatible physical quantities.

In general, Bohr considered the demands of complementarity in quantum mechanics to be logically on a par with the requirements of relativity in the theory of relativity. He believed that both theories were a result of novel aspects of the observation problem, namely the fact that observation in physics is context-dependent. This again is due to the existence of a maximum velocity of propagation of all actions in the domain of relativity and a minimum of any action in the domain of quantum mechanics. And it is because of these universal limits that it is impossible in the theory of relativity to make an unambiguous separation between time and space without reference to the observer (the context) and impossible in quantum mechanics to make a sharp distinction between the behavior of the object and its interaction with the means of observation (CC, p. 105).

Complementarity is first and foremost a semantic and epistemological reading of quantum mechanics that carries certain ontological implications. Bohr's view was, to phrase it in a modern philosophical jargon, that the truth conditions of sentences

ascribing a certain kinematic or dynamic value to an atomic object are dependent on the apparatus involved, in such a way that these truth conditions have to include reference to the experimental setup as well as the actual outcome of the experiment. This claim is called Bohr's *indefinability thesis* (Murdoch 1987; Faye 1991). Hence, those physicists who accuse this interpretation of operating with a mysterious collapse of the wave function during measurements haven't got it right. Bohr accepted the Born statistical interpretation because he believed that the ψ -function has only a symbolic meaning and does not represent anything real. It makes sense to talk about a collapse of the wave function only if, as Bohr put it, the ψ -function can be given a pictorial representation, something he strongly denied.

Indeed, Bohr, Heisenberg, and many other physicists considered complementarity to be the only rational interpretation of the quantum world. They thought that it gave us the understanding of atomic phenomena in accordance with the conditions for any physical description and the possible objective knowledge of the world. Bohr believed that atoms are real, but it remains a much debated point in recent literature what sort of reality he believed them to have, whether or not they are something beyond and different from what they are observed to be. Henry Folse argues that Bohr must operate with a distinction between a phenomenal and a transcendental object. The reason is that this is the only way it makes sense to talk about the physical disturbance of the atomic object by the measuring instrument as Bohr did for a while (Folse 1985, 1994). But Jan Faye has replied that Bohr gave up the disturbance metaphor in connection with his discussion of the EPR thought-experiment because he realized that it was misleading. Moreover, there is no further evidence in Bohr's writings indicating that Bohr would attribute intrinsic and measurement-independent state properties to atomic objects (though quite unintelligible and inaccessible to us) in addition to the classical ones being manifested in measurement (Faye 1991).

5. The Use of Classical Concepts

A central element in the Copenhagen Interpretation is Bohr's insistence on the use of classical concepts both with respect to describing experimental results and endowing quantum formalism with an empirical interpretation. The special cognitive status ascribed to the classical concepts is something Bohr stressed from the very beginning. Here is a quotation from 1934:

No more is it likely that the fundamental concepts of the classical theories will ever become superfluous for the description of physical experience. ... It continues to

be the application of these concepts alone that makes it possible to relate the symbolism of the quantum theory to the data of experience. (*ATDN*, p. 16)

Later he expressed the same view in an often quoted passage:

It is decisive to recognize that, however far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms. The argument is simply that by the word ‘experiment’ we refer to a situation where we can tell to others what we have done and what we have learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics. (*APHK*, p. 39)

Bohr saw the classical concepts as necessary for procuring unambiguous communication about what happens in the laboratory. Classical concepts are indispensable, because they enable physicists to describe observations in a clear common language, and because they are the ones by which the physicists connect the mathematical formalism with observational content.

Over the years, different authors have come up with different explanations of why Bohr thought that classical concepts were unavoidable for the description of quantum phenomena. Here we shall group those explanations in relation to five different philosophical frameworks: 1) Empiricism, 2) Kantianism, 3) Pragmatism, 4) Darwinianism, and 5) Experimentalism.

Empiricism. This view is represented by the logical positivists. They believed that the interpretation of any scientific theory should be grounded in empirical observations. No theory, according the positivists, is cognitively meaningful unless its terms can be connected to terms that are able to express results that would verify that theory. Observational terms refer directly to observable things or observable properties of physical objects, whereas theoretical terms are explicitly defined by correspondence rules connecting them with the observational terms. Hence classical terms, like position and momentum, are exactly such terms that enable physicist to ascribe a physical meaning to quantum mechanics.

Kantianism. Many philosophers and physicists have recognized a strong kinship between Kant and Bohr’s thinking or a direct Kantian influence on Bohr. In the thirties C.F. von Weizsäcker and Grete Hermann attempt to understand complementarity in the light of neo-Kantian ideas. As von Weizsäcker puts it many years later, “The alliance between Kantians and physicists was premature in Kant’s time, and still is; in Bohr, we begin to perceive its possibility”. A series of modern scholars (Folse 1985; Honner 1982, 1987; Faye 1991; Kaiser 1992; Chevalley 1994; Pringe 2009; Cuffaro 2010; Bitbol 2013, 2017; and Kauark-Leite 2017) has

also emphasized the Kantian parallels. Although these scholars find common themes, they also disagree to what extent Kantian or neo-Kantian ideas can be used as spectacles through which we may vision Bohr's understanding of quantum mechanics. On the other hand, Cuffaro (2010) holds that any proper "interpretation of Bohr should *start* with Kant", and that "complementarity follows naturally from a broadly Kantian epistemological framework." Kant's assumption was that our forms of intuition and our categories of thoughts constitute the transcendental conditions for the possibility of any objective experience. Thus, space and time are referred to as the forms of intuition, and the categories of understanding such as causation, unity, plurality, and totality are the a priori concepts which the mind imposes on the sense impressions that appear in our intuition. In a similar way, it is argued that Bohr saw concepts like space, time, causation, unity, and totality as a priori categories that was necessary for any objective description of quantum phenomena, and that classical physics was an explication and operationalization of these a priori concepts.

Pragmatism. Some scholars have advocated for a more pragmatic explanation of Bohr's thesis concerning the indispensability of classical concepts. Here the interpretation focuses on how we experimentally get to know something about atoms. We find out about atoms by interacting with atomic systems, not by picturing them, and the interaction are accounted for in terms of experiential categories. The pragmatists typically reject the a priori status of the mind's categories as they take them to be contingent. From a physical perspective it is a simple matter of facts that we need classical language to understand our scientific practise; it does not require any philosophical justification (Dieks 2017). Likewise, Dorato (2017) compares Bohr's indispensable thesis to Peter Strawson's descriptive metaphysics according to which we all share a common conceptual scheme about the experiential world which cannot be given a further justification. Also Folse notes, in a comparison between Bohr and I.C. Lewis, that classical concepts reflect our empirical needs and shared interests and may eventually change if these needs and interests change (Folse 2017). The common language together with the development of a physical clarification of some basic empirical concepts gave us the classical physics because such an improved language enables us to communicate in an unambiguous and objective manner about our observations. As Bohr puts it: "... even when the phenomena transcend the scope of classical physical theories, the account of the experimental arrangement and the recording of observations must be given in plain language, suitably supplemented by technical physical terminology. This is a clear logical demand, since the very word "experiment" refers to a situation where we can tell others what we have done and what we have learned." (*APHK*, p. 71). The use of classical concepts to

grasp the world is beneficial for understanding each other. Such empirical concepts provide us with an objective description of the function and outcome of physical experiments.

Darwinism. In several places Bohr speaks about the classical concepts as embodied in our common language, which is *adapted to* account for our physical experiences. The selection of the word “adapted to” seems to indicate that Bohr relied on Darwin’s theory of natural selection in his search for an explanation. The classical concepts are indispensable for the description of our experience because we are forced by nature to use a common language that is *adapted to* reporting our visual experiences, which again is a result of humans’ adaptation to their physical environment (Faye, 2017). Apart from Bohr’s use of the word “adapted to”, Bohr’s former assistant Leon Rosenfeld, who was an ardent defender of Bohr’s complementarity, explicitly suggests that “the complementary logic” is due to human evolution: “I suspect the development of a computing and communication system like our brain demands about that complexity of organization which has been reached by our own species in the course of evolution” (Rosenfeld, (1961 [1979]), p. 515). Natural selection installs certain permanent visual cognitive schemes in our predecessors, and this cognitive adaptation explains why these schemes, later reflected in our common language, gain a privileged epistemic status, and keep this status in physics in terms of refined classical concepts.

Experimentalism. Camilleri (2017) calls Bohr the philosopher of experiment. Others such as Perovic (2013) have also suggested that Bohr was more occupied by understanding the outcome of quantum experiments than by interpreting the quantum formalism. This view is substantiated in Perovic (2021) where he points to traditional induction as Bohr’s methods of constructing hypotheses from experimental data, just as he argues that this fact is a prerequisite for understanding Bohr’s view on correspondence and complementarity. However, Camilleri proposes in his paper that the challenge Bohr was facing was that, on the one hand, experimental observation requires a sharp separation of the experiment and the observed object, and, on the other hand, because of what we today call entanglement, “it is no longer possible sharply to distinguish between the autonomous behaviour of a physical object and its inevitable interaction with other bodies serving as measuring instruments” (CC, p. 84). So, according to Camilleri, Bohr solved this challenge by making a distinction between the function and the structure of an experiment.

Bohr’s central insight was that if a measuring instrument is to serve its *purpose of furnishing us with knowledge of an object* – that is to say, if it is to be described functionally – it must be described classically. Of course, it is always possible to

represent the experimental apparatus from a purely structural point of view as a quantum-mechanical system without any reference to its function. However, any functional description of the experimental apparatus, in which it is treated as a means to an end, and not merely as a dynamical system, must make use of the concepts of classical physics. (Camilleri, 2017, pp. 30–31)

This analysis explains not only why Bohr thought that classical concepts were indispensable for interpretational purposes, but also indicates why he thought that properties like momentum, position, and duration could be attributed only to an atom object in relation to a specific experimental arrangement. As Dieks (2017) mentions while denying any deeper philosophical motivation on Bohr's part: the use of classical concepts is part of the laboratory life. "This classical description is basically just the description in terms of everyday language, generalized by the addition of physics terminology, and it is the one we *de facto* use to describe our environment" (Dieks 2017). But because of quantum of action, symbolized by Planck's constant, the function of experiments that supply the physicists with exact information about space-time coordinations is incompatible with experiments whose function it is to supply them with exact information about energy and momentum.

Indeed, there are both similarities and overlaps between some of the proposed explanations concerning the indispensability of classical concepts. Yet, not all of the suggested explanations can be true. Even though the aim of Bohr's effort is to give an empirical interpretation of the quantum formalism, his empiricism is different from that of the logical positivists. He does not seek to reduce terms concerning theoretical entities to terms about sense-data or purely perceptual phenomena. He insists only that the empirical evidence physicists collect from their experiments on atomic objects has to be described in terms of the same concepts which were developed in classical mechanics in order for them to understand what the quantum theory is all about.

Nevertheless, the various explanations all give us some hints into the complexity of Bohr's thinking concerning the description of physical experiments. At different times, he seems to put emphasis on one aspect rather than another, depending on the specific context of discussion. Sometimes he was occupied with the interpretation of experiments, sometimes with the relationship between actual experiments and the formulation of quantum mechanics. In emphasizing the necessity of classical concepts for the description of quantum phenomena, Bohr might have been influenced by Kantian-like ideas or neo-Kantianism (Hooker, 1994). But if so, he was a naturalized or a pragmatized Kantian. The classical concepts are merely explications of common-sense concepts that are already a

result of our perceptual adaptation to the world. These concepts and the conditions of their application determine the conditions for objective knowledge. The discovery of the quantization of action has revealed to us, however, that we cannot apply these concepts to quantum objects as we did in classical physics. The use of classical concepts in the domain of quantum mechanics has to be restricted with respect to their use in classical mechanics. Now kinematic and dynamic properties (represented by conjugate variables) can be meaningfully ascribed to the object only in relation to some actual experimental results, whereas classical physics attributes such properties to the object regardless of whether we actually observe them or not. In other words, Bohr denied that classical concepts could be used to attribute properties to a physical world in-itself behind the perceptual phenomena, i.e. properties different from those being observed. In contrast, classical physics rests on an idealization, he said, in the sense that it assumes that the physical world has these properties in-itself, i.e. as inherent properties, independent of their actual observation.

6. The Interpretation of the Quantum Formalism

Classical concepts serve the important function of connecting the quantum mechanical symbolism with experimental observations. If one accepts that Bohr's grasp of physics began with his understanding of the role of physical experiments, this understanding had strong implications for his empirical interpretation of the quantum formalism. The modern scholarly debate has taken Bohr to be an instrumentalist, an objective anti-realist (Faye 1991), a phenomenological realist (Shomar 2008), or a realist of various sorts (Folse 1985, 1994; Favrholdt 1994; MacKinnon 1994; Howard 1994, 2004; Zinkernagel 2015, 2016). But very often the various participants do not give an exact specification of how they understand these terms and how these terms apply to Bohr's thinking. The whole discussion becomes confused because different authors use terms like "realism" and "antirealism" differently in relation to Bohr. For instance, Faye (1991) holds that Bohr is an entity realist but a non-representationalist concerning theories. Therefore he calls Bohr an objective antirealist. In contrast, Folse (1986) who also sees Bohr as both a entity realist and a theoretical non-representationalist calls him a realist. Moreover, Bohr himself would probably refuse to put any such labels on his own view.

It is certain that Bohr regarded atomic objects as real (*ATDN*, p. 93 and p. 103). Their existence has been confirmed by countless experiments. Hence, phrased in a modern terminology Bohr might be classified as an *entity realist* in the sense that experiments reveal their classical properties in relation to an experimental set-up. Such a view does not fit traditional instrumentalism where the introduction of

unobservable entities is a logical construction in order to classify various empirical observations together. But entity realism corresponds with objective anti-realism, phenomenological realist, and all other forms of realism because it does not indicate anything about one's attitude towards theories. A further issue is then how to interpret a physical theory. Does or doesn't the quantum formalism, according to Bohr, represent the world over and above being a tool for prediction?

Here are four statements which seem to show that Bohr was an instrumentalist concerning scientific theories in general and the quantum formalism in particular.

1. The purpose of scientific theories “is not to disclose the real essence of phenomena but only to track down, so far as it is possible, relations between the manifold aspects of experience” (*APHK*, p. 71).
2. “The ingenious formalism of quantum mechanics, which abandons pictorial representation and aims directly at a statistical account of quantum processes ...” (*CC*, p. 152).
3. “The formalism thus defies pictorial representation and aims directly at prediction of observations appearing under well-defined conditions” (*CC*, p. 172).
4. “The entire formalism is to be considered as a tool for deriving predictions of definite and statistical character ...” (*CC*, p. 144).

In these four statements Bohr mentions the absence of “pictorial representation” twice in relation to the quantum formalism. The term “pictorial representation” stands for a representation that helps us to visualize what it represents in contrast to “symbolic representation”. A pictorial representation is a formalism that has an isomorphic relation to the objects it represents such that the visualized structure of the representation corresponds to a similar structure in nature. Conversely, a symbolic representation does not stand for anything visualizable. It is an abstract tool whose function it is to calculate a result whenever this representation is applied to an experimental situation. With respect to the formalism of quantum mechanics it is particularly one's interpretation of the wave function that determines whether one thinks of it symbolically as a tool for calculation of statistical outcomes or thinks of it as representing a real physical field.

In a close reading of the Como-paper, Dennis Dieks reaches the conclusion that “The notion that the lecture is meant to promulgate an instrumentalist interpretation of quantum theory according to which the whole formalism possesses only mathematical and no physical descriptive content is thus immediately seen to sit uneasily with the textual evidence.” (Dieks 2017, p. 305).

In other words, Dieks goes against the more general interpretation of Bohr according to which Bohr only believed that the wave function formalism is a mere tool for prediction. Hans Halvorson (2019) expresses a similar view as Dieks does, arguing that even though Bohr used the word *symbolic* it should not be understood as if the wave function were “nonrepresentational” or “uninterpreted”. Halvorson thinks that we should read “symbolic” as philosophers do in the continental tradition going back to Kant, and he suggests with reference to Pringe (2014) that there might be parallels to Ernst Cassirer’s view on symbols. Just because Bohr writes off quantum formalism as a pictorial representation, it still gives us some insight into physical reality.

In the argument for his reading, Dieks points to another of Bohr’s argument against seeing Schrödinger’s wave function as representing anything real. This argument concerns the fact that the wave function in quantum mechanics cannot represent a three-dimensional entity.

Bohr himself tells us that his second argument, about the dimensionality of configuration space, is the most important one: “*above all* there can be no question of an immediate connexion with our ordinary conceptions because... the wave equation is associated with the so-called co-ordinate space.” In other words, the Schrödinger wave in the case of a many-particle system cannot be a physical wave in three-dimensional space (which would be an “ordinary conception”) since it “lives” in a high-dimensional mathematical space. (Dieks 2017, p. 308)

Then Dieks argues that even though this is an argument against wave function realism, it is not an argument that excludes the wave function from containing information about the quantum world. Dieks compares this argument to the one that denies phase space realism. “We can consistently deny the physical reality of phase space and still be realists with respect to particles. So we should not mistake Bohr’s argument for the symbolic character of the wave function for an argument in favor of instrumentalism *tout court*” (Dieks 2017, p. 308). The difference between classical many-particles system placed in a phase space and a system of quantum objects placed in the configuration space is, however, that the description of many particles in phase space can be decomposed into a description of single particles in three-dimensional physical space, whereas the sum of the quantum waves associated with many particles in configuration space yields yet another superimposed quantum wave, which cannot be decomposed into a description of single particles in three-dimensional space. Dieks then continues to show how the structural features of the quantum formalism guided Bohr in his interpretation of quantum mechanism. Likewise, he argues that Bohr’s pronouncements on the meaning of quantum mechanics should first of all be seen as responses to concrete

physical problems, rather than as expressions of a preconceived philosophical doctrine. His analysis results in a finding that Bohr's qualitative interpretation is in line with modern non-collapse theories.

7. Misunderstandings of Complementarity

Complementarity has been commonly misunderstood in several ways, some of which shall be outlined in this section. First of all, earlier generations of philosophers and scientists have often accused Bohr's interpretation of being positivistic or subjectivistic. Today philosophers have almost reached a consensus that it is neither. There are, as many have noticed, both typically realist as well as antirealist elements involved in it, and it has affinities with Kant or neo-Kantianism. The influence of Kant or Kantian thinking on Bohr's philosophy seems to have several sources. Some have pointed to the German tradition from Hermann von Helmholtz (Chevalley 1991, 1994; Brock 2003); others have considered the Danish philosopher Harald Høffding to be the missing link to Kantianism (Faye 1991; Christiansen 2006; and Pringe 2020). A dissenting opinion is Favrholt (1992).

But because Bohr's view on complementarity has wrongly been associated with positivism and subjectivism, much confusion still seems to stick to the Copenhagen interpretation. Don Howard (2004) argues, however, that what is commonly known as the Copenhagen interpretation of quantum mechanics, regarded as representing a unitary Copenhagen point of view, differs significantly from Bohr's complementarity interpretation. He holds that "the Copenhagen interpretation is an invention of the mid-1950s, for which Heisenberg is chiefly responsible, [and that] various other physicists and philosophers, including Bohm, Feyerabend, Hanson, and Popper, hav[e] further promoted the invention in the service of their own philosophical agendas" (p. 669).

More recently, Mara Beller (1999) argued that Bohr's statements are intelligible only if we presume that he was a radical operationalist or a simple-minded positivist. In fact, complementarity was established as the orthodox interpretation of quantum mechanics in the 1930s, a time when positivism was prevalent in philosophy of science, and some commentators have taken the two to be closely associated. During the 1930s Bohr was also in touch with some of the leading neopositivists or logical empiricists such as Rudolph Carnap, Otto Neurath, Philip Frank, and the Danish philosopher Jørgen Jørgensen (Faye and Jaksland 2021a). Although their anti-metaphysical approach to science may have had some influence on Bohr (especially around 1935 during his final discussion with Einstein about the completeness of quantum mechanics), one must recall that Bohr always

saw complementarity as a necessary response to the indeterministic description of quantum mechanics due to the quantum of action. The quantum of action was an empirical discovery, not a consequence of a certain epistemological theory, and Bohr thought that indeterminism was the price to pay to avoid paradoxes. Never did Bohr appeal to a verificationist theory of meaning; nor did he claim classical concepts to be operationally defined. But it cannot be denied that some of the logical empiricists rightly or wrongly found support for their own philosophy in Bohr's interpretation and that Bohr sometimes confirmed them in their impressions (Faye 2008).

Second, many physicists and philosophers see the reduction of the wave function as an important part of the Copenhagen interpretation. This may be true for people like Heisenberg. But Bohr never talked about the collapse of the wave packet. Nor did it make sense for him to do so because this would mean that one must understand the wave function as referring to something physically real. Only if one can interpret a quantum measurement as an interaction between an instrument and an object, whose state is literally represented by Schrödinger's wave function, and therefore taken to contain all potential values of observation, does it make sense to claim that the measurement forces the object to manifest one of these potential values. Indeed, such a literal interpretation of the state vector implies that these values are somehow intrinsically present in the object with a certain probability all at once. In contrast, Bohr believed that particular kinematical and dynamical properties are relational because their attribution to a quantum system makes sense only in relation to a particular experimental set-up and therefore that these numerical properties could have a specific value only during a measurement.

Third, Bohr flatly denied the ontological thesis that the subject has any direct impact on the outcome of a measurement. Hence, when he occasionally mentioned the subjective character of quantum phenomena and the difficulties of distinguishing the object from the subject in quantum mechanics, he did not think of it as a problem confined to the observation of atoms alone. For instance, he stated that already "the theory of relativity reminds us of the subjective character of all physical phenomena" (*ATDN*, p. 116). Rather, by referring to the subjective character of quantum phenomena he was expressing the epistemological thesis that all observations in physics are in fact context-dependent. There exists, according to Bohr, no view from nowhere in virtue of which quantum objects can be described.

Fourth, although Bohr had spoken about "disturbing the phenomena by observation," in some of his earliest papers on complementarity, he never had in mind the observer-induced collapse of the wave packet. Later he always talked about the interaction between the object and the measurement apparatus which was

taken to be completely objective. Thus, Schrödinger's Cat did not pose any riddle to Bohr. The cat would be dead or alive long before we open the box to find out. What Bohr claimed was, however, that the state of the object and the state of the instrument are dynamically inseparable during the interaction. Moreover, the atomic object does not possess any state separate from the one it manifests at the end of the interaction because the measuring instrument establishes the necessary conditions under which it makes sense to use the state concept.

It was the same analysis that Bohr applied in answering the challenge of the EPR-paper. Bohr's reply was that we cannot separate the dynamical and kinematical properties of a joint system of two particles until we actually have made a measurement and thereby set the experimental conditions for the ascription of a certain state value (CC, p. 80). Bohr's way of addressing the puzzle was to point out that individual states of a pair of coupled particles cannot be considered in isolation, in the same way as the state of the object and the state of the instrument are dynamically inseparable during measurements. Thus, based on our knowledge of a particular state value of the auxiliary body A, being an atomic object or an instrument, we may then infer the state value of the object B with which A once interacted (Faye 1991, pp. 182–183). It therefore makes sense when Howard (2004, p. 671) holds that Bohr considered the post-measurement joint state of the object and the measuring apparatus to be entangled as in any other quantum interaction involving an entangled pair.

Finally, when Bohr insisted on the use of classical concepts for understanding quantum phenomena, he did not believe, as it is sometimes suggested, that macroscopic objects or the measuring apparatus always have to be described in terms of the dynamical laws of classical physics. The use of the classical concepts is necessary, according to Bohr, because by these we have learned to communicate to others about our physical experience. The classical concepts are merely a refinement of everyday concepts of position and action in space and time. However, the use of the classical concepts is not the same in quantum mechanics as in classical physics. Bohr was well aware of the fact that, on pains of inconsistency, the classical concepts must be given "a suitable quantum-theoretical re-interpretation," before they could be employed to describe quantum phenomena (ATDN, p. 8).

8. The Divergent Views

The Copenhagen interpretation is not a homogenous view. This insight has begun to emerge among historians and philosophers of science over the last ten to fifteen years. Both James Cushing (1994) and Mara Beller (1999) take for granted the

existence of a unitary Copenhagen interpretation in their social and institutional explanation of the once total dominance of the Copenhagen orthodoxy; a view they personally find unconvincing and outdated partly because they read Bohr's view on quantum mechanics through Heisenberg's exposition. But historians and philosophers of science have gradually realized that Bohr's and Heisenberg's pictures of complementarity on the surface may appear similar but beneath the surface diverge significantly. Don Howard (2004, p. 680) goes as far as concluding that "until Heisenberg coined the term in 1955, there was no unitary Copenhagen interpretation of quantum mechanics." The term apparently occurs for the first time in Heisenberg (1955). In addition, Howard also argues that it was Heisenberg's exposition of complementarity, and not Bohr's, with its emphasis on a privileged role for the observer and observer-induced wave packet collapse that became identical with that interpretation. Says he: "Whatever Heisenberg's motivation, his invention of a unitary Copenhagen view on interpretation, at the center of which was his own, distinctively subjectivist view of the role of the observer, quickly found an audience" (p. 677). This audience included people like David Bohm, Paul Feyerabend, Norwood Russell Hanson, and Karl Popper who used Heisenberg's presentation of complementarity as the target for their criticism of the orthodox view. However, it should also be mentioned that in later work, Feyerabend (1968, 1969) was one of the first philosophers who gave a painstaking analysis of complementarity in order to clear up the myth of it being unintelligible. Feyerabend urged philosophers and physicists to go back to Bohr and read him carefully.

Following up on Don Howard's research, Kristian Camilleri (2006, 2007) points to the fact that complementarity was originally thought by Bohr (in his Como-paper) to exist between the space-time description and the causal description of the stationary states of atoms — and not between different experimental outcomes of the free electron. So the formulation of complementarity was restricted to the concept of stationary states because only there does the system have a well-defined energy state independent of any measurement. This observation deserves general recognition. But when Bohr rather soon thereafter began analysing the double slit experiment in his discussion with Einstein (1930), he had to extend his interpretation to cover the electron in interaction with the measuring apparatus.

Camilleri then shows how Heisenberg's view of complementarity, in spite of Heisenberg's own testimony, radically differs from Bohr's. As Heisenberg understood complementarity between the space-time description and causal description, it holds between the classical description of experimental phenomena and the description of the state of the system in terms of the wave function. A

quotation from Heisenberg (1958, p. 50) shows how much he misunderstood Bohr in spite of their previously close working relationship.

Bohr uses the concept of ‘complementarity’ at several places in the interpretation of quantum theory ... The space-time description of the atomic events is complementary to their deterministic description. The probability function obeys an equation of motion as did the co-ordinates in Newtonian mechanics; its change in the course of time is completely determined by the quantum mechanical equation; it does not allow a description in space and time but breaks the determined continuity of the probability function by changing our knowledge of the system.

So, where Bohr identified the causal description with the conservation of energy, Heisenberg saw it as the deterministic evolution of Schrödinger’s ψ -function. In other words, Heisenberg, in contrast to Bohr, believed that the wave equation gave a causal, albeit probabilistic description of the free electron in configuration space. It also explains why so many philosophers and physicists have identified the Copenhagen interpretation with the mysterious collapse of the wave packet. The transition from a causal description in terms of the evolution of the ψ -function to a classical space-time description is characterized by the discontinuous change that occurs by the act of measurement. According to Heisenberg, these two modes of description are complementary.

In another study Ravi Gomati (2007) agrees with Howard’s exposition in arguing that Bohr’s interpretation of complementarity and the textbook Copenhagen interpretation (i.e. wave-particle duality and wave packet collapse) are incompatible. More recently, Henderson (2010) has come to a similar conclusion. He makes a distinction between different versions of Copenhagen interpretations based on statements from some of the main characters. On one side of the spectrum there is Bohr who did not think of quantum measurement in terms of a collapse of the wave function (for a contrasting view see Jens Heber 2005; and partly Zinkernagel 2016); in the middle we find Heisenberg talking about the collapse as an objective physical process but thinking that this couldn’t be analyzed any further because of its indeterministic nature, and at the opposite side Johann von Neumann and Eugene Wigner argued that the human mind has a direct influence on the reduction of the wave packet. Unfortunately, von Neumann’s dualistic view has become part of the Copenhagen methodology by people opposing this interpretation.

9. The Measurement Problem

Some physicists and philosophers of science see the measurement problem as a real puzzle with respect to the Copenhagen interpretation. On the one hand, we have that the wave function evolved deterministically according to Schrödinger's equation as a linear superposition of different states; and the other hand an actual measurement always detect one definite state. To be or not to be in a superposition; that's the question.

Apparently, we are living in a quantum world since everything is constituted by atomic and subatomic particles. Hence classical physics seems merely to be a useful approximation to a world which is quantum mechanical on all scales. Such a view, which many modern physicists support, can be called quantum fundamentalism (Zinkernagel 2015, 2016). It can be defined as a position containing two components: (1) everything in the Universe is fundamentally of quantum nature (the ontological component); and (2) everything in the Universe is ultimately describable in quantum mechanical terms (the epistemological component). Thus, we may define quantum fundamentalism to be the position holding that everything in the world is essentially quantized and that the quantum theory gives us a literal description of this nature. The basic assumption behind quantum fundamentalism is that the structure of the formalism, in this case the wave function, corresponds to how the world is structured. For instance, according to the wave function description every quantum system may be in a superposition of different states because a combination of state vectors is also a state vector. Now, assuming that both the quantum object and the measuring apparatus are quantum systems that each can be described by a wave function, it follows that their entangled state would likewise be represented by a state vector. Then the challenge is, of course, how we can explain why the pointer of a measuring instrument enters a definite (and not a superposition) position, as experience tells us, whenever the apparatus interacts with the object. In a nutshell this is the measurement problem.

The Copenhagen interpretation is often taken to subscribe to a solution to the measurement problem that has been offered in terms of John von Neumann's projection postulate. In 1932 [1996], von Neumann suggested that the entangled state of the object and the instrument collapses to a determinate state whenever a measurement takes place. This measurement process (a type 1-process as he called it) could not be described by quantum mechanics; quantum mechanics can only described type-2 processes (i.e., the development of a quantum system in terms of Schrödinger's equation). In his discussion of the measurement problem, von Neumann then distinguished between (i) the system actually observed; (ii) the

measuring instrument; and (iii) the actual observer. He argues that during a measurement the actual observer gets a subjective perception of what is going on that has a non-physical nature, which distinguishes it from the observed object and the measuring instrument. However, he holds on to psycho-physical parallelism as a scientific principle, which he interprets such that there exists a physical correlate to any extra-physical process of the subjective experience. So in every case where we have a subjective perception we must divide the world into the observed system and the observer. But where the division takes place is partly arbitrary. According to von Neumann, it is contextual whether the dividing line is drawn between the description of the observed object (i) and the measuring instrument together with the observer (ii) + (iii), or it is drawn between the description of the observed object together with the measuring instrument, i.e., (i) + (ii), and the observer (iii). In other words, von Neumann argues that the observer can never be included in a type 2-process description, but the measuring instrument may sometime be part of a type 2-process, although it gives the same result with respect to the observed object (i). An important consequence of von Neumann's solution to the measurement problem is that a type 1-process takes place only in the presence of the observer's consciousness. Furthermore, even when von Neumann considers the situation in which the descriptions of (i) and (ii) are combined, he talks about the interaction between the physical system (i) + (ii) and an abstract *ego* (iii) (Neumann 1932 [1996], Ch VI). Therefore, the mind seems to play an active role in forming a type 1-process, which would be incompatible with psycho-physical parallelism.

Indeed, within philosophy of mind one cannot consistently maintain both psycho-physical parallelism and the existence of an interaction between the brain and the mind. So it is no wonder that Eugene Wigner (1967) followed up on the suggestion of the mind's interaction by proposing that what causes a collapse of the wave function is the mind of the observer. But Wigner never explained how it was possible for something mental to produce a material effect like the collapse of a quantum system. The measuring problem led to the famous paradox of Schrödinger's cat and later to the one of Wigner's friend. Although von Neumann's and Wigner's positions are usually associated with the Copenhagen Interpretation, such views were definitely not Bohr's as we shall see in a moment.

Quantum fundamentalists must indeed be ready to explain why the macroscopic world appears classical. An alternative to von Neumann's projection postulate is the claim that the formalism should be read literally and that measurements (classical outcomes) do not describe the world as it really is. But there are ontological cost, which is significant to some. In one interpretation the world divides into as many worlds as there are possible measurement outcomes each time

a system is observed or interacts with another system. Other fundamentalists had hoped that the decoherence program might come up with an appropriate explanation. The decoherence theory sees entanglement to exist not only between object and the measurement but also as something which includes the environment. If Bohr had known the idea of decoherence, he would probably have had no objection to it, as several authors have pointed to decoherence as a natural dynamical extension of his view that measurements is an irreversible amplification process (Schlosshauer and Camilleri 2015, 2017; Bächtold 2017, Tanona 2017; and Dieks 2017). However, it is generally agreed that decoherence does not solve the measurement problem (Bacciagaluppi 2016; Zinkernagel 2011). This might seem as if von Neumann's projection postulate has to be reintroduced as a dynamical factor to explain why one and only one measurement result appears. However, as Dieks (2017) argues, Bohr's interpretation could be understood as a non-collapse interpretation, since "the superposition does not have an empirical meaning independently of its interpretation via classically described experiments, so no replacement by another mathematical state is needed. We just have to interpret the formulas correctly." In spite of that there is no general agreement to what extent Bohr opposed quantum fundamentalism.

Time and again Bohr emphasized that the epistemological distinction between the instrument and the object is necessary because this is the only way one can functionally make sense of a measurement. The epistemic purpose of a measuring instrument is to yield information about an object separated from the instrument itself. It is also generally agreed that Bohr didn't treat the classical world of the measuring instrument as epistemically separated from quantum object along the line of a microscopic and macroscopic division. Where the line is drawn is a matter of convenience. Thus, Bohr sometimes included parts of the measuring instrument into the system to which the quantum mechanical description should be applied. In one place Bohr gave the following characteristics of the situation:

In the system to which the quantum mechanical formalism is applied, it is of course possible to include any intermediate auxiliary agency employed in the measuring processes. Since, however, all those properties of such agencies which, according to the aim of the measurement, have to be compared with corresponding properties of the object, must be described on classical lines, their quantum mechanical treatment will for this purpose be essentially equivalent with a classical description. The question of eventually including such agencies within the system under investigation is thus purely a matter of practical convenience, just as in classical physical measurements; and such displacements of the section between object and measuring instruments can therefore never involve any arbitrariness in

the description of a phenomenon and its quantum mechanical treatment.
(Bohr, CC, p. 104)

This is an important passage because it indicates that Bohr believed that quantum mechanics has a universal applicability in the sense that it can be used to describe macroscopic objects as well. It also tell us that whether or not parts of the macroscopic measuring apparatus are treated as a part of the quantum object depends on pragmatic or contextual conditions, but their quantum mechanical treatment should result in a description that corresponds to a similar classical description. Based on quotes like the one above, Don Howard (1994) concludes that Bohr was not only an ontological quantum fundamentalist but in fact also a sort of an epistemological one. He believes that one can make Bohr's requirement that measuring apparatus and the experimental results have to be described in ordinary language supplemented with the terminology of classical physics consistent with ontological quantum fundamentalism. According to him, Bohr never considered the measuring instrument as a classical object. Moreover, he thinks that this implies that Bohr had to understand the use of classical concepts differently from what scholars usually think. He reinterprets Bohr in terms of quantum states called "mixtures". Howard believes that with respect to an experimental context in which an instrument interacts with an object, Bohr didn't understand them as being in an entangled state but being separated in a mixture state. The consequence would be that the instrument and the object exist in a definite quantum state since such a state could be represented as a product of the wave function for the instrument and for the object.

But, as Maximilian Schlosshauer and Kristian Camilleri (2008 (Other Internet Resources), 2011) have pointed out, this does not solve the measurement problem. Howard does not explain under which circumstances one can move from a quantum system-cum-measuring apparatus being in a non-separable state to a mixture of separated states. Therefore one cannot be sure that the measuring apparatus is in a definite state and its pointer in a definite place. Some philosophers seem to argue that Bohr was an ontological but not an epistemological quantum fundamentalist. For instance, "Bohr believed in the fundamental and universal nature of quantum mechanics, and saw the classical description of the apparatus as a purely epistemological move, which expressed the fact that a given quantum system is being used as a measuring device" (Landsman 2007); and in a similar vein: "One is left with the impression from Bohr's writings that the quantum-classical divide is a necessary part of the epistemological structure of quantum mechanics" (Schlosshauer and Camilleri 2008 (Other Internet Resources), 2015). So Klaas Landsman (2006, 2007) accepts Howard's suggestion that Bohr is an ontological quantum fundamentalist but he rejects that Bohr should be considered

an epistemological quantum fundamentalist. Landsman argues that Bohr held that the measuring instrument should be described in classical terms since the results of any measurement like in classical physics would always have a definite value. However, Landsman agrees that Bohr understood all objects as essentially quantum mechanical objects.

However, one could argue that Howard and Landsman miss the epistemic nature of Bohr's view on ontological issues. Apparently, Bohr might say that quantum mechanics is correctly understood a theory of measurement, a theory about how the quantum world appears to us, and not how this world is in itself. Bohr mentioned more than once that physics is not about finding the essence of nature but about describing the phenomena in an unambiguous way. In the foreground of Bohr's thinking was the (1) the need of classical concepts for the description of measuring results; (2) non-separability due to the entanglement of the system and the measuring instrument; (3) the contextual nature of the measurements of complementary properties; and (4) the symbolic character of the quantum formalism. One has to take all four components into consideration if one wants to understand Bohr's solution to the classical-quantum problem.

According to this understanding of Bohr as an empirical realist but a transcendental idealist, we are in quantum mechanics confronted with the "impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the very conditions under which the phenomena appear" (*APHK*, p. 210). This is definitely a non-classical feature which is described by quantum mechanics alone. In his response to the EPR-paper, Bohr strongly rejected that this form of interaction could be regarded as a mechanical influence. The influence was on the conditions of description, i.e. the experimental conditions under which it makes sense to apply classical concepts. But during a measurement we need to separate the system from the measuring instrument and the environment for pragmatic reasons. The pragmatic reasons seem to be reasonably clear. The outcomes of whatever experiment always yield a definite value, so the entanglement of object and the measurement instrument described by the quantum formalism only lasts epistemically until the interaction between object and instrument stops. The quantum formalism can predict the statistical outcome of these interactions but it cannot say anything about the trajectory of objects.

Bohr's firmness about the use of classical concepts for the descriptions of measurement can be seen as his response to the measurement problem. This problem arises from the fact that quantum mechanics itself cannot account for why experiments on objects in a state of superposition always produce a definite

outcome. Hence if one does not argue for spontaneous collapse of the wave function, hidden variables, or many worlds, one needs to supplement quantum mechanics with a classical description of measuring instruments in terms of clocks and rods. Henrik Zinkernagel (2015, 2016) may seem to get close to Bohr's view when he argues that Bohr not so much solved the measuring problem as he dissolved it. According to his interpretation, Bohr believed in a quantum world, but only relative to a particular classical description and a certain classical world. The distinction between classical and quantum (both ontic and epistemic) is contextual. He thinks that the measurement problem is ultimately a consequence of ontological quantum fundamentalism (that everything is quantum). Because if everything is quantum – and correctly described by quantum formalism (what else would it mean to call everything quantum?) – then a measurement ends up in a superposition whether we describe the apparatus classical or not. One could say with Zinkernagel that Bohr believed all objects can be treated as quantum objects, but they cannot all be treated as quantum objects at the same time. Borrowing a conception from the two Russian physicists, Landau and Lifshitz, Zinkernagel claims that only some parts of the measuring device are entangled with the object in question, but those parts which are not entangled exists as a classical object. Depending on the context, objects cannot be treated as quantum objects in those situations in which they acts as measuring apparatuses. In these situations the classical treatment of the measuring device provides us with a frame of reference of space and time with respect to which an atomic object has a position, and, *mutatis mutandis*, with respect to which it has energy and momentum. Such a frame of reference is necessary for our ability to define and measure a particular property. In Bohr's own words: "in each case [of measurement] some ultimate measuring instruments, like the scales and clocks which determine the frame of space-time coordination on which, in the last resort, even the definitions of momentum and energy quantities rest, must always be described entirely on classical lines, and consequently kept outside the system subject to quantum mechanical treatment" (*CC*, p. 104). What characterizes a frame of reference is that it establishes the conditions for the ascription of a well-defined position or a well-defined momentum, and treated classically measuring instruments act exactly as frames of reference. The implication is that Bohr did not exclude the application of quantum theory to any system. Every system can in principle be treated quantum mechanically, but since we always need a frame of reference to describe experimental outcomes, not all systems can be treated quantum mechanically at once.

In this debate Dorato (2017) stresses the fact that by making explicit reference to Einstein's presentation of his special theory of relativity, Bohr regarded quantum

mechanics as a theory of principle. This explains both Bohr's epistemic reliance on the domain of classical physics and his ban of any attempt to construct classical objects from quantum objects. Despite this position Dorato argues that in order to justify his entity realism and anti-instrumentalist interpretations, Bohr also needed to postulate something ontologically distinct from the realm of quantum mechanics, a claim that creates the well-known problem of defining in a non-ambiguous and exact way the cut between the classical and the quantum realm. By following Zinkernagel, he claims that this problem is somewhat softened by Bohr's contextualist theory of measurement. However, Bohr's holism, according to which the measuring device and quantum object are in state of entanglement, is in objective tension with Bohr's thesis of an ontological distinction, especially in virtue of the fact that by referring to the interaction between the quantum and the classical system as an irreversible physical process, Bohr seems to need a constructive approach to quantum mechanics that he wants to avoid.

Nonetheless, the question is to what extent Bohr really believed that the classical world is not only epistemically but also ontologically different from the quantum world? If he did not make an ontological distinction, there would be no contradiction between his epistemic view that the outcome of measurement needs to be described classically but that the apparatus ontologically is just as much a quantum object as the object under investigation. So when Bohr regarded quantum mechanics as a rational generalization of classical physics, he always thought of it as a way to secure the epistemic validity of quantum mechanics and not a way to save a classical ontology. Directly addressing Zinkernagel's analysis, Dieks (2017) strongly argues that there can be little doubt that Bohr believed that quantum mechanics is universal in the sense that Heisenberg's indeterminacy relation applies to both micro- and macroscopic systems due to the quantum of action. Classical mechanics is a mathematical approximation. Moreover, Bohr believed for epistemic reasons that we had to use classical language because this language is a refinement of our everyday language, which is adapted to describe our sensory experience and therefore the only language that can endow the quantum formalism with an empirical content. Hence, according to Dieks, Bohr assumed that it is only an epistemic necessity to describe "*some* systems classically in order to have a pragmatic starting point for the treatment of other systems." Bohr's demand of using classical concepts for epistemic reasons has no implications for his view that macroscopic objects are quantum objects. Measuring devices are not classical objects even though we need classical concepts to describe our general physical experiences and the outcome of quantum experiments. So Dieks concludes that the interaction between the measuring device and the quantum object determines, in the classical textbook examples, whether position or momentum talk can be carried

over to the quantum object that is measured. The measuring device itself, if macroscopic and under ordinary circumstances (so that it really is a measuring device that can be used by us) allows both position and momentum talk in its own description. The measurement interaction determines which correlations are forged with the micro-world.

10. Complementarity, Decoherence, and Probabilities

Everyone agrees that decoherence does not provide physicists with an explanation of why a measurement selects one particular value rather than another given all the statistically possible values represented by the wave function. But the question is still open regarding in what way Bohr thought that any measuring process rests on a dynamical interaction between the quantum system and the measuring apparatus, in spite of the fact that a descriptive separation between them had to be made if the value offered by the measuring apparatus has to be a recording of the quantum system. The closest Bohr came to such a dynamical interaction was when he maintained that the measuring process leaves an *irreversible* mark on the instrument. In spite of such remarks, Bohr never discussed his interpretation in modern terms of “entanglement” or “decoherence”.

While Schrödinger coined the term “entanglement”, Howard (2021) argues that the word refers to an unavoidable feature of quantum mechanics, which most physicists recognized from the very start. Einstein for one already realized this in connection his concept of light quanta with respect to the photoelectric effect. Bohr’s formulation of entanglement was the uncontrollable interaction between the object and the measuring apparatus. For instance, when Bohr presented his view on complementarity in Como 1927 he wrote:

the quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. (*ATDN*, p. 54)

As Howard (2021) points out, we know that the interaction Bohr here talked about, is not the one Heisenberg had in mind when he presented his electron microscope in which light used to detect the electron disturbs the electron. Such an explanation was exactly the suggestion that Bohr, in his discussion with Heisenberg, had turned against before the latter published his classical paper on the indeterminacy relation.

However, Bohr's formulation has often been misread as giving support to a classical form of disturbance, and the expression "uncontrollable interaction" may have misled Einstein and other physicists to believe that quantum mechanics was incomplete, because to be considered as a disturbance such an interaction may be thought to change a pre-existing value. The first time Bohr publicly distanced himself from such a disturbance interpretation of interaction between the object and the instrument was in his reply to the EPR-paper. In this case, the entanglement under consideration is no longer the one between an object and the measuring instrument but between two subsystems A and B. Nonetheless, presenting an experiment in which an object first passes either a fixed or a movable single slit diaphragm, and then another diaphragm with a double slit, Bohr showed with his example how the outcome of particular measurement on subsystem A influences the outcome of measurement on B. (If the first diaphragm is fixed in order to measure the object's position, one observes on the screen behind the second diaphragm an interference pattern, but if first diaphragm is movable in order to determine through which one of the two slits the object travelled, the interference pattern disappears).

Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical state of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system*. (CC, p. 80)

Here Bohr explicitly denied that the uncontrollable interaction involves any form of disturbance, which is otherwise characteristic of well-separated objects in classical states. The uncontrollable interaction he had in mind was what in modern term is a state in which the system and the measuring instrument is entangled. The entanglement between the object and the measuring apparatus prevents the object as well as the detector from having a well-defined, independent state. Hence, the entanglement prompted Bohr to think that the use of classical concepts depended on the experimental context and that was therefore complementary.

Today most philosophers agree that ontologically, Bohr was a quantum fundamentalist, holding that the quantum mechanical description applies to microscopic as well as macroscopic objects. However, he also insisted that measuring results should be described in classical terms due to the epistemic separation we have to make between the entangled object and the measuring instrument. This is how we can communicate our observation. The question then arises: how is it that the world appears in a classical manner?

In 1970 quantum mechanics was enriched with a new notion when Hans Dieter Zeh (1970) introduced ‘decoherence’. Since then, many physicists have taken part in developing this notion, and today the processes behind decoherence plays a huge role; for instance, in the construction of quantum computers. The view behind decoherence is that quantum mechanics rules all the way up and down but that any object is always interacting with a very large number of environmental degrees of freedom such that the interference terms corresponding to macroscopically distinct states disappear. In other words, we do not see Schrödinger’s cat in a superposition in which it is both dead and alive.

Camilleri and Schlosshauer (2015) and Schlosshauer and Camilleri (2017) have argued that Bohr’s philosophy and the insights brought about by decoherence theory may not just coexist peacefully. Decoherence may also be seen as supplying the dynamical justification for the distinction that Bohr held to be epistemically necessary, between the “classical system” serving as the measuring apparatus and the “quantum object.” However, Howard (2021) goes a step further as he argues that Bohr believed as part of his view of complementarity that Schrödinger’s dynamics of pure joint states of the object-instrument-environment interaction is statistically and observationally equivalent to the context-dependent mixture over eigenstates picked out by measurements. Howard therefore argues: (1) complementarity and decoherence assume that quantum is ontologically fundamental; (2) classicality emerges from quantum behavior; and (3) decoherence confirms Bohr’s view that measurement is a practical irreversible process where information dissipates through the observed system due to the fact that decoherence produces a single macroscopic mark. His conclusion is that the “environmentally-induced decoherence (which is not really decoherence, but only a semblance thereof) was, all along, the real point toward which Bohr was gesturing with the doctrines of complementarity” (p. 171). Hence, Howard concludes that decoherence is not only in agreement with complementarity, but complementarity is a consequence of the fact that quantum mechanics with the Born rule is a statistical theory and so is the decoherence dynamics, and therefore we cannot expect that decoherence should be able to explain a specific determinate outcome of a measurement. However, he also concludes that the context-dependent mixture he reads into Bohr’s view provides us with “the sought-for simulacrum of classicality”. Whether Bohr would support the last remark that the classical world is an epistemic illusion is certainly debatable.

Howard’s reading seems to rest on an understanding of Schrödinger’s wave function as having a representational role of referring to dynamical quantum states. However, Bohr never seems to have spoken about quantum states other than in connection with the stationary states of an atom. From the very beginning, Bohr

focused on the transition probabilities of Heisenberg's matrix mechanics more than on Schrödinger's wave mechanics, a view that did not change after the interpretation of the wave function in terms of the Born rule. Consider the following statements by Bohr:

According to the two alternative procedures, quantum mechanical calculations may be performed either by representing the variables with matrices with elements referring to the individual transitions between two states of the system or by making use of the so called wave equation, the solutions of which refer to these states and allow us to derive probabilities for the transitions between them. The entire formalism is to be considered as a tool for deriving predictions of definite or statistical character, as regards information obtainable under experimental conditions described in classical terms and specified by means of parameters entering into the algebraic or differential equations of which the matrices or the wave-functions, respectively, are solutions. These symbols themselves, as is indicated already by the use of imaginary numbers, are not susceptible to pictorial interpretation; and even derived real functions like densities and currents are only to be regarded as expressing the probabilities for the occurrence of individual events observable under well defined experimental conditions. (CC, pp. 143–144)

Here Bohr equates matrices and wave functions because these two sets of mathematical symbols both express probabilities in quantum mechanics in the form of predictions of measurement outcomes. Following David Wallace (2016) in distinguishing between representational and probabilistic interpretations of quantum states, Jeffery Bub (2017) argues that Bohr interpreted them probabilistically, which the above quotation seems to support.

Bohr's primary insight was to see that quantum mechanics is quite unlike any theory we have dealt with before in the history of physics, and so explanation in such a post-classical theory can't be the sort of representational explanation we are familiar with in a theory that is commutative or Boolean at the fundamental level.

As Bub (2016) explains, "quantum probabilities can't be understood in the classical or Boolean sense as quantifying ignorance about pre-measurement value of observable" (p. 223). Thus, when Heisenberg constructed his matrix mechanics, he realized that kinematical and dynamical quantities in quantum mechanics are non-commutative. This implies, according to Bub, that these properties must be described by a family of "intertwined" Boolean algebras, each member corresponding to a set of commuting observables, where intertwinedness excludes the possibility of constructing a more inclusive Boolean algebra. Although Bohr did not speak about complementarity in terms of Boolean algebras, Bub suggests that this is exactly what Bohr had in mind when he insisted that we needed to use

classical terms in the description of measurement outcomes. On the macroscopic level, depending on the experimental context, the various outcomes belong to incompatible Boolean frames; on the microscopic level randomness and entanglement rules, something which quantum mechanics explains in terms of probabilistic constraints on events depicted through the geometry of Hilbert space.

This information-theoretic interpretation of complementarity, according to Bub (2022), abstains from introducing decoherence to explain quantum probabilities, which are ‘perfectly new and sui generis aspects of physical reality’ and ‘uniquely given from the start’, as von Neumann had pointed out. In addition to this, Bub (2017) argues that “The collapse, as a conditionalization of the quantum state, is something you put in by hand after observing the actual outcome. The physics doesn’t give it to you.” This might well be Bohr’s view. No matter what, the divergences between the various analyses show that there is no consensus about how Bohr’s view on complementarity and measurement plays out with respect to one’s favorite quantum foundation.

11. New Perspectives

After the 1950s a number of alternative interpretations to Bohr’s complementarity were articulated and they all found their proponents among physicists and philosophers of science. The Copenhagen interpretation started to lose ground to other interpretations such as Bohm’s interpretation, the many worlds interpretation, the modal interpretation and the decoherence interpretation, which have been more in vogue the last couple of decades. But parallel with the growing awareness of the essential differences between Bohr’s and Heisenberg’s understanding of quantum mechanics several philosophers of science have revitalised Bohr’s view on complementarity. Around the millennium a new recognition of the Copenhagen interpretation has emerged.

Rob Clifton and Hans Halvorson (1999, 2002) argue that Bohm’s interpretation of quantum mechanics can be seen as a special case of Bohr’s complementarity interpretation if it is assumed that all measurements ultimately reduce to positions measurement. Originally Jeffrey Bub and Clifton (1996) were able to demonstrate (given some idealized conditions) that Bohr’s complementarity and Bohm’s mechanics fall under their uniqueness theorem for no-collapse interpretations. Clifton and Halvorson improve this result by showing that Bohr’s idea of position and momentum complementarity can be expressed in terms of inequivalent representations in the C^* -algebraic formalism of quantum mechanics. It turns out that either position or momentum are dynamically significant, but it is not permissible to assume that position and momentum are both dynamically

significant in any single context. From these assumptions they conclude that Bohm's hidden variables are none other than the "value states" that the complementarity interpretation postulates if position measurement were always dynamically significant, but this metaphysical restriction is not, as their results indicate, demanded by the physics. Rather, Clifton and Halvorson (1999) and Halvorson (2004) believe that complementarity may give us a realist interpretation of quantum field theory.

Philosophers have also started to explore the idea of decoherence in relation to Bohr's view about "the inseparability of the behavior of the object and the interaction with the measuring instrument" or "the uncontrollable interaction between the atomic system and measurement apparatus." (Schlosshauer and Camilleri 2011, 2017; Camilleri and Schlosshauer 2015; Bächtold 2017; and Tanona 2017). Although Bohr assumed that the measuring apparatus is altogether a quantum mechanical system, he nevertheless believed that the instrument could be approximately described by classical *theory*. Among the scholars just mentioned there is a general agreement that the notion of decoherent is coherent with Bohr's view about the quantum-classical division and adds a dynamical explanation of quantum-to-classical transition which Bohr's own exposition lacked. Also attempts to clear up the structural relationship between Bohr's view and Hugh Everett's "relative state"-interpretation have been carried out; a relationship which at some points is much closer than usually thought (Bacciagaluppi 2017).

Another insight into Bohr's view of complementarity is due to Michael Dickson (2001, 2002). By using the contemporary theory of reference frames in quantum theory, he proves that Bohr's response to the EPR thought-experiment was in fact the correct one. Moreover, he also maintains that Bohr's discussions of spin, a property much less frame dependent than position and momentum, were very different from his discussions of the latter, and based on these differences he offers a Bohrian account of Bell's theorem and its significance.

A re-assessment of Bohr's philosophy of quantum mechanics is made by Whitaker (2004) on the basis of Clifton and Halvorson's and Dickson's works and in the light of quantum information theory. Besides these attempts to apply Bohr's notion of complementarity to the contemporary discussions of the interpretation of quantum mechanics and quantum field theory there is an ongoing attempt to understand Bohr's idea of symbolic representation (Tanona, 2004a, 2004b) and his notion of complementarity with respect to trends in post-modern philosophy and general epistemology such as poststructuralism, deconstructivism, feminism and cultural studies (Honner 1994; Plotnitsky 1994; Barad 2007; and Katsumori 2011).

Faye and Jaksland (2023b) offers a critical discussion of Barad's interpretation of Bohr.

Bibliography

References to Work by Bohr

CW Bohr, N. (1972–2006), *Collected Works, Vol. 1–12*, Amsterdam: Elsevier.

ATDN Bohr, N. (1934/1987), *Atomic Theory and the Description of Nature*, reprinted as *The Philosophical Writings of Niels Bohr, Vol. I*, Woodbridge: Ox Bow Press.

APHK Bohr, N. (1958/1987), *Essays 1932–1957 on Atomic Physics and Human Knowledge*, reprinted as *The Philosophical Writings of Niels Bohr, Vol. II*, Woodbridge: Ox Bow Press.

Essays Bohr, N. (1963/1987), *Essays 1958–1962 on Atomic Physics and Human Knowledge*, reprinted as *The Philosophical Writings of Niels Bohr, Vol. III*, Woodbridge: Ox Bow Press.

CC Bohr, N. (1998), *Causality and Complementarity*, supplementary papers edited by Jan Faye and Henry Folse as *The Philosophical Writings of Niels Bohr, Vol. IV*, Woodbridge: Ox Bow Press.

Many-Worlds Interpretation of Quantum Mechanics

First published Sun Mar 24, 2002; substantive revision Thu Aug 5, 2021

The Many-Worlds Interpretation (MWI) of quantum mechanics holds that there are many worlds which exist in parallel at the same space and time as our own. The existence of the other worlds makes it possible to remove randomness and action at a distance from quantum theory and thus from all physics. The MWI provides a solution to the [measurement problem](#) of quantum mechanics.

- [1. Introduction](#)
- [2. Definitions](#)
 - [2.1 What is “A World”?](#)
 - [2.2 Who am I?](#)
- [3. Correspondence Between the Formalism and Our Experience](#)
 - [3.1 The Quantum State of a Macroscopic Object](#)
 - [3.2 The Quantum State of a World](#)
 - [3.3 The Quantum State of the Universe](#)
 - [3.4 FAPP](#)
 - [3.5 Preferred Basis](#)
 - [3.6 The Measure of Existence](#)
- [4. Probability in the MWI](#)
 - [4.1 Probability from Uncertainty](#)
 - [4.2 Illusion of Probability from Post-Measurement Uncertainty](#)
 - [4.3 Probability Postulate from Symmetry Arguments](#)
- [5. Tests of the MWI](#)
- [6. Objections to the MWI](#)
 - [6.1 Ockham’s Razor](#)
 - [6.2 The Problem of Preferred Basis](#)

- [6.3 The Wave Function is not Enough](#)
 - [6.4 Derivation of the Probability Postulate](#)
 - [6.5 Social Behavior of a Believer in the MWI](#)
 - [7. Why the MWI?](#)
 - [Bibliography](#)
 - [Preprints](#)
 - [Academic Tools](#)
 - [Other Internet Resources](#)
 - [Related Entries](#)
-

1. Introduction

The fundamental idea of the MWI, going back to Everett 1957, is that there are myriads of worlds in the Universe in addition to the world we are aware of. In particular, every time a quantum experiment with different possible outcomes is performed, all outcomes are obtained, each in a different newly created world, even if we are only aware of the world with the outcome we have seen. The reader can split the world right now using this interactive [quantum world splitter](#). The creation of worlds takes place everywhere, not just in physics laboratories, for example, the explosion of a star during a supernova.

There are numerous variations and reinterpretations of the original Everett proposal, most of which are briefly discussed in the entry on [Everett's relative state formulation of quantum mechanics](#). Here, a particular approach to the MWI (which differs from the popular “actual splitting worlds” approach in De Witt 1970) will be presented in detail, followed by a discussion relevant for many variants of the MWI.

The MWI consists of two parts:

- i. A theory which yields the time evolution of the quantum state of the (single) Universe.
- ii. A prescription which sets up a correspondence between the quantum state of the Universe and our experiences.

Part (i) states that the ontology of the universe is a quantum state, which evolves according to the Schrödinger equation or its relativistic generalization. It is a rigorous mathematical theory and is not problematic philosophically. Part (ii) involves “our experiences” which do not have a rigorous definition. An additional difficulty in setting up (ii) follows from the fact

that human languages were developed at a time when people did not suspect the existence of parallel worlds.

The mathematical part of the MWI, (i), yields less than mathematical parts of some other theories such as Bohmian mechanics. The Schrödinger equation itself does not explain why we experience definite results in quantum measurements. In contrast, in Bohmian mechanics the mathematical part yields almost everything, and the analog of (ii) is very simple: it is the postulate according to which only the “Bohmian positions” (and not the quantum wave) correspond to our experience. The Bohmian positions of all particles yield the familiar picture of the (single) world we are aware of. The simplicity of part (ii) of Bohmian mechanics comes at the price of adding problematic physical features to part (i), e.g., the nonlocal dynamics of Bohmian trajectories.

2. Definitions

2.1 What is “A World”?

A world is the totality of macroscopic objects: stars, cities, people, grains of sand, etc. in a definite classically described state.

The concept of a “world” in the MWI belongs to part (ii) of the theory, i.e., it is not a rigorously defined mathematical entity, but a term defined by us (sentient beings) to describe our experience. When we refer to the “definite classically described state” of, say, a cat, it means that the position and the state (alive, dead, smiling, etc.) of the cat is specified according to our ability to distinguish between the alternatives, and that this specification corresponds to a classical picture, e.g., no superpositions of dead and alive cats are allowed in a single world.

Another concept, which is closer to Everett’s original proposal, see Saunders 1995, is that of a relative, or perspectival world defined for every physical system and every one of its states: following Lewis 1986 we call it a *centered world*. This concept is useful when a world is centered on a perceptual state of a sentient being. In this world, all objects which the sentient being perceives have definite states, but objects that are not under observation might be in a superposition of different (classical) states. The advantage of a centered world is that a quantum phenomenon in a distant galaxy does not split it, while the advantage of the definition presented here is that we can consider a world without specifying a center; our usual language is just as useful for describing worlds that existed at times when there were no sentient beings.

The concept of a world in the MWI is based on the layman’s conception of a world; however, several features are different. Obviously, the definition of the world as *everything that exists* does not hold in the MWI. “Everything that exists” is the Universe, and there is only one Universe. The Universe incorporates many worlds similar to the one the layman is familiar with. A layman believes that our present world has a unique past and future. According to the MWI, a world defined at some moment of time corresponds to a unique world at a time in the past, but to a multitude of worlds at a time in the future.

2.2 Who am I?

I am an object, such as the Earth, a cat, etc. “I” is defined at a particular time by a complete (classical) description of the state of my body and of my brain. “I” and “Lev” do not refer to the same things (even though my name is Lev). At the present moment there are many different “Lev”s in different worlds (not more than one in each world), but it is meaningless to say that now there is another “I”. I have a particular, well defined past: I correspond to a particular “Lev” in 2020, but not to a particular “Lev” in the future: I correspond to a multitude of “Lev”s in 2030. This correspondence is seen in my memory of a unique past: a “Lev” in 2021 shares memories with one particular “Lev” in 2020 but with multiple “Lev”s in 2030. In the framework of the MWI it is meaningless to ask: Which “Lev” in 2030 will I be? I will correspond to them all. Every time I perform a quantum experiment (with several outcomes) it only seems to me that a single definite result is obtained. Indeed, the “Lev” who obtains this particular result thinks this way. However, this “Lev” cannot be identified as the only “Lev” after the experiment. The “Lev” before the experiment corresponds to multiple “Lev”s who obtain all possible results.

Although this approach to the concept of personal identity seems somewhat unusual, it is plausible in the light of the critique of personal identity by Parfit 1986. Parfit considers some artificial situations in which a person splits into several copies, and argues that there is no good answer to the question: “Which copy is me?” He concludes that personal identity is not what matters when the observer divides. Saunders and Wallace 2008a argue that based on the semantics of Lewis 1986 one can find a meaning for this question. However, in their reply (Saunders and Wallace 2008b) to Tappenden 2008 they emphasise that their work is not about the nature of “I”, but about “serviceability”. Indeed, as it will be explained below, I should behave as if “Which copy is me?” is a legitimate question.

3. Correspondence Between the Formalism and Our Experience

We should not expect to have a detailed and complete explanation of our experience in terms of the wave function of 10^{33} particles that we and our immediate environment are made of. We just have to be able to draw a basic picture which is free of paradoxes. There are many attempts to provide an explanation of what we see based on the MWI or its variants in Lockwood 1989, Gell-Mann and Hartle 1990, Albert 1992, Saunders 1993, Penrose 1994, Chalmers 1996, Deutsch 1996, Joos *et al.* 2003, Schlosshauer 2007, Wallace 2012, Cunningham 2014, Vaidman 2016a, Zurek 2018, Vaidman 2019, and Tappenden 2019a. A sketch of the connection between the wave function of the Universe and our experience follows.

3.1 The Quantum State of a Macroscopic Object

The basis for the correspondence between the quantum state (the wave function) of the Universe and our experience is the description that physicists give in the framework of

standard quantum theory for objects composed of elementary particles. Elementary particles of the same kind are identical (see the elaborate discussion in the entry on [identity and individuality in quantum theory](#)). The essence of an object is the (massively entangled) quantum state of its particles and not the particles themselves. One quantum state of a set of elementary particles might be a cat and another state of the same particles might be a small table. An object is a spatial pattern of such a quantum state. Clearly, we cannot now write down an exact wave function of a cat. We know, to a reasonable approximation, the wave function of the elementary particles that constitute a nucleon. The wave function of the electrons and the nucleons that together make up an atom is known with even better precision. The wave functions of molecules (i.e. the wave functions of the ions and electrons out of which molecules are built) are well studied. A lot is known about biological cells, and physicists are making progress in the quantum representation of biological systems Cao et. al 2020. Out of cells we construct various tissues and then the whole body of a cat or a table. So, let us denote the quantum state of a macroscopic object constructed in this way $|\Psi\rangle^{\text{OBJECT}}.|\Psi\rangle^{\text{OBJECT}}$.

In our construction $|\Psi\rangle^{\text{OBJECT}}|\Psi\rangle^{\text{OBJECT}}$ represents an object in a definite state and position. According to the definition of a world we have adopted, in each world the cat is in a definite state: either alive or dead. Schrödinger’s experiment with the cat leads to a splitting of worlds even before opening the box. Note that in the centered world approach, the superposed Schrödinger’s cat is a member of the single world of the observer before she opens the sealed box with the cat. The observer directly perceives the facts related to the experiment and deduces that the cat is in a superposition.

Formally, the quantum state of an object which consists of NN particles is defined in $3N3N$ dimensional configuration space, see Albert 1996, 2015. However, in order to understand our experience, it is crucial to make a connection to 33 dimensional space, see Stoica 2019. We only experience objects defined in $3D3D$ -space. The causes of our experience are interactions, and in nature there are only local interactions in three spatial dimensions. These interactions can be expressed as couplings to some macroscopic variables of the object described by quantum waves well localized in $3D3D$ -space, which are in a product with the relative variables state of the object (like entangled electrons in atoms) and other parts of the object, see Vaidman 2019 (Sec. 5.6). Another way to bridge between the wave function of the object and our experience of that object is the three-dimensional picture of the density of the wave function of molecules of the macroscopic object which has the familiar geometrical form of the object. Note that in some other interpretations of quantum mechanics, similar densities are given additional ontological significance (Allori *et al.* 2014.)

3.2 The Quantum State of a World

The wave function of all particles in the Universe corresponding to any particular world will be a product of the states of the sets of particles corresponding to all objects in the world multiplied by the quantum state $|\Phi\rangle|\Phi\rangle$ of all the particles that do not constitute “objects”. Within a world, “objects” have definite macroscopic states by fiat:

$$(1)|\Psi^{\text{WORLD}}\rangle=|\Psi\rangle_{\text{OBJECT 1}}|\Psi\rangle_{\text{OBJECT 2}}\dots|\Psi\rangle_{\text{OBJECT N}}|\Phi\rangle(1)|\Psi^{\text{WORLD}}\rangle=|\Psi\rangle_{\text{OBJECT 1}}|\Psi\rangle_{\text{OBJECT 2}}\dots|\Psi\rangle_{\text{OBJECT N}}|\Phi\rangle$$

The product state is only for variables which are relevant for the macroscopic description of the objects. There might be some entanglement between weakly coupled variables like nuclear spins belonging to different objects. In order to keep the form of the quantum state of the world (1), the quantum state of such variables should belong to $|\Phi\rangle, |\Phi\rangle$.

Consider a text-book description of quantum measurements based on the von Neumann 1955 approach according to which each quantum measurement ends up with the collapse of the wave function to the eigenstate of the measured variable. The quantum measurement device must be a macroscopic object with macroscopically different states corresponding to different outcomes. In this case, the MWI all-particles wave function corresponding to a world with a particular outcome is the same as in the von Neumann theory provided there is a collapse to the wave function with this outcome. The von Neumann 1955 analysis helps in understanding the correspondence between the wave function and our perception of the world. However, as Becker 2004 explains, the status of the wave function for von Neumann is not ontological as in the MWI described here, but epistemic: it summarises information about the results of measurements.

In most situations, only macroscopic objects are relevant to our experience. However, today's technology has reached a point in which interference experiments are performed with single particles. In such situations a description of a world with states of only macroscopic objects, such as sources and detectors, is possible but cumbersome. Hence it is fruitful to add a description of some microscopic objects. Vaidman 2010 argues that the proper way to describe the relevant microscopic particles is by the two-state vector which consists of the usual, forward evolving state specified by the measurement in the past and a backward evolving state specified by the measurement in the future. Such a description provides a simple explanation of the weak trace the particles leave, Vaidman 2013.

3.3 The Quantum State of the Universe

The quantum state of the Universe (i.e. the Universal wave function) can be decomposed into a superposition of terms corresponding to different worlds:

$$(2)|\Psi^{\text{UNIVERSE}}\rangle=\sum\alpha^i|\Psi^{\text{WORLD } i}\rangle(2)|\Psi^{\text{UNIVERSE}}\rangle=\sum\alpha^i|\Psi^{\text{WORLD } i}\rangle$$

Different worlds correspond to different classically described states of at least one object. Different classically described states correspond to orthogonal quantum states. Therefore, different worlds correspond to orthogonal states: all states $|\Psi^{\text{WORLD } i}\rangle, |\Psi^{\text{WORLD } j}\rangle$ are mutually orthogonal and consequently, $\sum|\alpha^i|^2=1, \sum|\alpha^i|^2=1$ (here we include as a “world” a situation in which there are no macroscopic objects).

3.4 FAPP

The construction of the quantum state of the Universe in terms of the quantum states of objects presented above is only approximate; it is good only *for all practical*

purposes (FAPP). Indeed, the concept of an object itself has no rigorous definition: should a mouse that a cat just swallowed be considered as a part of the cat? The concept of a “definite position” is also only approximately defined: how far should a cat be displaced for it to be considered to exist in a different position? If the displacement is much smaller than the quantum uncertainty, it must be considered to exist in the same place, because in this case the quantum state of the cat is almost the same and the displacement is undetectable in principle. But this is only an absolute bound, because our ability to distinguish various locations of the cat is far from this quantum limit. Furthermore, the state of an object (e.g. alive or dead) is meaningful only if the object is considered for a period of time. In our construction, however, the quantum state of an object is defined at a particular time. In fact, we have to ensure that the quantum state will have the shape of the object not only at that time, but for some period of time. Splitting of the world during this period of time is another source of ambiguity because there is no precise definition of when the splitting occurs. The time of splitting corresponds to the time of the collapse in the approach given by von Neumann 1955. He provided a very extensive discussion showing that it does not matter when exactly the collapse occurs, and this analysis shows also that it does not matter when the splitting in the MWI occurs.

The reason that it is possible to propose only an approximate prescription for the correspondence between the quantum state of the Universe and our experience is essentially the same reason for the claim of Bell 1990 that “ordinary quantum mechanics is just fine FAPP”. The concepts we use: “object”, “measurement”, etc. are not rigorously defined. Bell and many others were looking (until now in vain) for a “precise quantum mechanics”. Since it is not enough for a physical theory to be just fine FAPP, a quantum mechanics needs rigorous foundations. The MWI has rigorous foundations for (i), the “physics part” of the theory; only part (ii), corresponding to our experience, is approximate (just fine FAPP). But “just fine FAPP” means that the theory explains our experience for any possible experiment, and this is the goal of (ii). See Wallace 2002, 2010a, 2012 for more arguments why a FAPP definition of a world is enough.

3.5 Preferred Basis

The mathematical structure of the theory (i) allows infinitely many ways to decompose the quantum state of the Universe into a superposition of orthogonal states. The basis for the decomposition into world states follows from the definition of a world composed of objects in definite positions and states (“definite” on the scale of our ability to distinguish them). In the alternative approach, the basis of a centered world is defined directly by an observer. Therefore, given the nature of the observer and her concepts for describing the world, the particular choice of the decomposition (2) follows (up to a precision which is good FAPP, as required). If we do not ask why we are what we are, and why the world we perceive is what it is, but only how we can explain relations between the events we observe in our world, then the problem of the preferred basis does not arise: we and the concepts of our world define the preferred basis.

But if we do ask why we are what we are, we can explain more. Looking at the details of the physical world, the structure of the Hamiltonian, the value of the Planck constant, etc., one

can understand why the sentient beings we know are of a particular type and why they have their particular concepts for describing their worlds. The main argument is that the locality of interactions yields the *stability* of worlds in which objects are well localized. The small value of the Planck constant allows macroscopic objects to be well localized for a long period of time. Worlds corresponding to localized quantum states $|\Psi^{\text{WORLD } i}\rangle$ do not split for a long enough time such that sentient beings can perceive the locations of macroscopic objects. By contrast, a “world” obtained in another decomposition, e.g., the “world +” which is characterized by the relative phase of a superposition of states of macroscopic objects being in macroscopically distinguishable

states AA and BB, $1/\sqrt{2}(|\Psi^A\rangle + |\Psi^B\rangle)|\Phi\rangle$, $1/2(|\Psi^A\rangle + |\Psi^B\rangle)|\Phi\rangle$, splits immediately, during a period of time which is much smaller than the perception time of any feasible sentient being, into two worlds: the new “world+” and the

“world−”: $1/\sqrt{2}(|\Psi^A\rangle - |\Psi^B\rangle)|\Phi'\rangle$, $1/2(|\Psi^A\rangle - |\Psi^B\rangle)|\Phi'\rangle$. This is the phenomenon

of [decoherence](#) which has attracted enormous attention in recent years, e.g., Joos *et al.* 2003, Zurek 2003, Schlosshauer 2007, Wallace 2012, Riedel 2017, Schlosshauer 2019, Boge 2019, Saunders forthcoming-a also in the “decoherent histories” framework of Gell-Mann and Hartle 1990, see Saunders 1995 and Riedel *et al.* 2016.

3.6 The Measure of Existence

There are many worlds existing in parallel in the Universe. Although all worlds are of the same physical size (this might not be true if we take into account the quantum aspects of early cosmology), and in every world sentient beings feel as “real” as in any other world, there is a sense in which some worlds are larger than others. Vaidman 1998 describes this property as the *measure of existence* of a world.

There are two aspects of the measure of existence of a world. First, it quantifies the ability of the world to interfere with other worlds in a gedanken experiment, as expounded at the end of this section. Second, the measure of existence is the basis for introducing an *illusion of probability* in the MWI as described in the next chapter. The measure of existence is the parallel of the probability measure discussed in Everett 1957 and pictorially described in Lockwood 1989 (p. 230).

Given the decomposition (2), the measure of existence of the world i is $\mu^i = |\alpha^i|^2$, $\mu_i = |\alpha_i|^2$. It can also be expressed as the expectation value of $P_i P_i$, the projection operator on the space of quantum states corresponding to the actual values of all physical variables describing the world i :

$$(3) \mu^i = \langle \Psi^{\text{UNIVERSE}} | P_i | \Psi^{\text{UNIVERSE}} \rangle. (3) \mu_i = \langle \Psi^{\text{UNIVERSE}} | P_i | \Psi^{\text{UNIVERSE}} \rangle.$$

Note, that although the measure of existence of a world is expressed using the quantum state of the Universe (2), the concept of measure of existence, as the concept of a world belongs to part (ii) of the MWI, the bridge to our experience.

“I” also have a measure of existence. It is the sum of the measures of existence of all different worlds in which I exist. Note that I do not directly experience the measure of my

existence. I feel the same weight, see the same brightness, etc. irrespectively of how tiny my measure of existence might be.

My current measure of existence is relevant only for gedanken situations like Wigner's friend Wigner 1961 (recently revived by Frauchiger and Renner 2018) which demonstrates the meaning of the measure of existence of a world as a measure of its ability to interfere with other worlds. If I am a friend of Wigner, a gedanken superpower who can perform interference experiments with macroscopic objects like people, and I perform an experiment with two outcomes A and B such that two worlds will be created with different measures of existence, say $2\mu^A = \mu^B$, $2\mu^A = \mu^B$, then there is a difference between Lev A and Lev B in how Wigner can affect their future through the interference of worlds. Both Lev A and Lev B consider performing a new experiment with the same device. Wigner can interfere the worlds in such a way that Lev A (the one with a smaller measure of existence) will not have the future with result A of the second experiment. However, Wigner cannot prevent the future result A from Lev B, see Vaidman 1998 (p. 256).

4. Probability in the MWI

The probability in the MWI cannot be introduced in a simple way as in quantum theory with collapse. However, even if there is no probability in the MWI, it is possible to explain our illusion of apparent probabilistic events. Due to the identity of the mathematical counterparts of worlds, we should not expect any difference between our experience in a particular world of the MWI and the experience in a single-world universe with collapse at every quantum measurement.

4.1 Probability from Uncertainty

The difficulty with the concept of probability in a deterministic theory, such as the MWI, is that the only possible meaning for probability is an *ignorance probability*, but there is no relevant information that an observer who is going to perform a quantum experiment is ignorant about. The quantum state of the Universe at one time specifies the quantum state at all times. If I am going to perform a quantum experiment with two possible outcomes such that standard quantum mechanics predicts probability 1/3 for outcome A and 2/3 for outcome B, then, according to the MWI, both the world with outcome A and the world with outcome B will exist. It is senseless to ask: "What is the probability that I will get A instead of B?" because I will correspond to both "Lev"s: the one who observes A and the other one who observes B.

To solve this difficulty, Albert and Loewer 1988 proposed the Many Minds interpretation (in which the different worlds are only in the minds of sentient beings). In addition to the quantum wave of the Universe, Albert and Loewer postulate that every sentient being has a continuum of minds. Whenever the quantum wave of the Universe develops into a superposition containing states of a sentient being corresponding to different perceptions, the minds of this sentient being evolve randomly and independently to mental states corresponding to these different states of perception (with probabilities equal to the quantum probabilities for these states). In particular, whenever a measurement is performed by an

observer, the observer's minds develop mental states that correspond to perceptions of the different outcomes, i.e. corresponding to the worlds A or B in our example. Since there is a continuum of minds, there will always be an infinity of minds in any sentient being and the procedure can continue indefinitely. This resolves the difficulty: each "I" corresponds to one mind and it ends up in a state corresponding to a world with a particular outcome. However, this solution comes at the price of introducing additional structure into the theory, including a genuinely random process.

Saunders 2010 claims to solve the problem without introducing additional structure into the theory. Working in the Heisenberg picture, he uses appropriate semantics and mereology according to which distinct worlds have no parts in common, not even at early times when the worlds are qualitatively identical. In the terminology of Lewis 1986 (p. 206) we have the divergence of worlds rather than overlap. Wilson 2013, 2020 develops this idea by introducing a framework called "indexicalism", which involves a set of distinct diverging "parallel" worlds in which each observer is located in only one world and all propositions are construed as self-locating (indexical). In Wilson's words, "indexicalism" allows us to vindicate treating the weights as a candidate objective probability measure. However, it is not clear how this program can succeed, see Marchildon 2015, Harding 2020, Tappenden 2019a. It is hard to identify diverging worlds in our experience and there is nothing in the mathematical formalism of standard quantum mechanics which can be a counterpart of diverging worlds, see also Kent 2010 (p. 345). In the next section, the measure of existence of worlds is related to subjective ignorance probability.

There are more proposals to deal with the issue of probability in the MWI. Barrett 2017 argues that for a derivation of the Probability Postulate it is necessary to add some assumptions to unitary evolution. For example, Weissman 1999 has proposed a modification of quantum theory with additional non-linear decoherence (and hence with even more worlds than in the standard MWI) which can lead asymptotically to worlds of equal mean measure for different outcomes. Hanson 2003, 2006 proposed decoherence dynamics in which observers of different worlds "mangle" each other such that an approximate Born rule is obtained. Van Wesep 2006 used an algebraic method for deriving the probability rule, whereas Buniy *et al.* 2006 used the decoherent histories approach of Gell-Mann and Hartle 1990. Waegell and McQueen 2020 considered probability based on the ontology of 'local worlds' introduced by Waegell 2018, which is a concept inspired by the approach of Deutsch and Hayden 2000.

4.2 Illusion of Probability from Post-Measurement Uncertainty

Vaidman 1998 introduced the ignorance probability of an agent in the framework of the MWI in a situation of post-measurement uncertainty, see also Tappenden 2011, Vaidman 2012, Tipler 2014, 2019b, Schwarz 2015. It seems senseless to ask: "What is the probability that Lev in the world AA will observe AA?" This probability is trivially equal to 1. The task is to define the probability in such a way that we could reconstruct the prediction of the standard approach, where the probability for AA is 1/3. It is indeed senseless to ask *you* what

is the probability that Lev in the world AA will observe AA, but this might be a meaningful question when addressed to Lev in the world of the outcome AA. Under normal circumstances, the world AA is created (i.e. measuring devices and objects which interact with measuring devices become localized according to the outcome A)A) before Lev is aware of the result AA. Then, it is sensible to ask this Lev about his probability of being in world AA. There is a definite outcome which this Lev will see, but he is ignorant of this outcome at the time of the question. In order to make this point vivid, Vaidman 1998 proposed an experiment in which the experimenter is given a sleeping pill before the experiment. Then, while asleep, he is moved to room AA or to room BB depending on the results of the experiment. When the experimenter has woken up (in one of the rooms), but before he has opened his eyes, he is asked “In which room are you?” Certainly, there is a matter of fact about which room he is in (he can learn about it by opening his eyes), but he is ignorant about this fact at the time of the question.

This construction provides the ignorance interpretation of probability, but the value of the probability has to be postulated:

Probability Postulate

An observer should set his subjective probability of the outcome of a quantum experiment in proportion to the total measure of existence of all worlds with that outcome.

This postulate (named the *Born-Vaidman rule* by Tappenden 2011) is a counterpart of the collapse postulate of the standard quantum mechanics according to which, after a measurement, the quantum state collapses to a particular branch with probability proportional to its squared amplitude. (See the section on the measurement problem in the entry on [philosophical issues in quantum theory](#).) However, it differs in two aspects. First, it parallels only the second part of the collapse postulate, the Born Rule, and second, it is related only to part (ii) of the MWI, the connection to our experience, and not to the mathematical part of the theory (i).

The question of the probability of obtaining A makes sense for Lev in world A before he becomes aware of the outcome and for Lev in world B before he becomes aware of the outcome. Both “Lev”s have the same information on the basis of which they should give their answer. According to the probability postulate they will give the *same* answer: $1/3$ (the relative measure of existence of the world A)A). Since Lev before the measurement is associated with two “Lev”s after the measurement who have identical ignorance probability concepts for the outcome of the experiment, one can define the probability of the outcome of the experiment to be performed as the ignorance probability of the successors of Lev for being in a world with a particular outcome.

The “sleeping pill” argument does not reduce the probability of an outcome of a quantum experiment to a familiar concept of probability in the classical context. The quantum situation is genuinely different. Since all outcomes of a quantum experiment are realized, there is no probability in the usual sense. Nevertheless, this construction explains the illusion of probability. It leads believers in the MWI to behave according to the following principle:

Behavior Principle

We care about all our successive worlds in proportion to their measures of existence.

With this principle our behavior should be similar to the behavior of a believer in the collapse theory who cares about possible future worlds in proportion to the probability of their occurrence.

The important part of the Probability Postulate is the supervenience of subjective probability on the measure of existence. Given this supervenience, the proportionality follows naturally from the following argument. By the assumption, if after a quantum measurement all the worlds have equal measures of existence, the probability of a particular outcome is simply proportional to the number of worlds with this outcome. The measures of existence of worlds are, in general, not equal, but the experimenters in all the worlds can perform additional specially tailored auxiliary measurements of some variables such that all the new worlds will have equal measures of existence. The experimenters should be completely indifferent to the results of these auxiliary measurements: their only purpose is to split the worlds into “equal-weight” worlds. Then, the additivity of the measure of existence yields the Probability Postulate.

There are many other arguments (apart from the empirical evidence) supporting the Probability Postulate. Gleason’s 1957 theorem about the uniqueness of the probability measure uses a natural principle that the probability of an outcome is independent of splitting into parallel worlds. Tappenden 2000, 2017 adopts a different semantics according to which “I” live in all branches and have “distinct experiences” in different “superslices”. He uses “weight of a superslice” instead of “measure of existence” and argues that it is intelligible to associate probabilities according to the Probability Postulate. Exploiting a variety of ideas in decoherence theory such as the relational theory of tense and theories of identity over time, Saunders 1998 argues for the “identification of probability with the Hilbert Space norm” (which equals the measure of existence). Page 2003 promotes an approach named *Mindless Sensationalism*. The basic concept in this approach is a conscious experience. He assigns *weights* to different experiences depending on the quantum state of the universe, as the expectation values of presently-unknown positive operators corresponding to the experiences (similar to the measures of existence of the corresponding worlds). Page writes “... experiences with greater weights exist in some sense more ...” (2003, 479). In all of these approaches, the postulate is introduced through an analogy with treatments of time, e.g., the measure of existence of a world is analogous to the duration of a time interval. Note also Greaves 2004 who advocates the “Behavior Principle” on the basis of the decision-theoretic reflection principle related to the next section.

4.3 Probability Postulate from Symmetry Arguments

In an ambitious work Deutsch 1999 claimed to derive the Probability Postulate from the quantum formalism and classical decision theory. In Deutsch’s argument the notion of probability is operationalised by being reduced to an agent’s betting preferences. So an agent who is indifferent between receiving \$20 on those branches where spin “up” is observed and receiving \$10 on all branches *by definition* is deemed to give probability 1/2 to the spin-up

branches. Deutsch then attempts, using some symmetry arguments, to prove that the only rationally coherent strategy for an agent is to assign these operationalised “probabilities” to equal the quantum-mechanical branch weights. Wallace 2003, 2007, 2010b, 2012 developed this approach by making explicit the tacit assumptions in Deutsch’s argument. In the most recent version of these proofs, the central assumptions are (i) the symmetry structure of unitary quantum mechanics; (ii) that an agent’s preferences are consistent across time; (iii) that an agent is indifferent to the fine-grained branching structure of the world per se. Early criticisms of the Deutsch-Wallace approach focussed on circularity concerns (Barnum *et al.* 2000, Baker 2007, Hemmo and Pitowsky 2007). As the program led to more explicit proofs, criticism turned to the decision-theoretic assumptions being made (Lewis 2010, Albert 2010, Kent 2010, Price 2010). The analysis of the Deutsch-Wallace program continues in a flurry of (mostly critical) papers (Adlam 2014, Dawid and Thébault 2014, Dawid and Thébault 2015, Dizadji-Bahmani 2015, Jansson 2016, Read 2018, Mandolesi 2018, Mandolesi 2019, Araujo 2019, Brown and Ben Porath 2020, Saunders forthcoming-b).

Zurek 2005 offers a new twist to the Born rule derivation based on the permutation symmetry of states corresponding to worlds with equal measures of existence. He considered entangled systems and relies on “envariance” symmetry: a unitary evolution of a system which can be undone by the unitary evolution of the system it is entangled with. Zurek assumes that a manipulation of the second system does not change the probability of the measurement on the first system. The swap of the states of the system swaps the probabilities of the outcomes, because the outcomes are correlated with the other systems, where nothing has been changed. Since the swaps of the two systems lead to the original state, the probabilities should be unchanged, but they have swapped, so they must be equal.

Sebens and Carroll 2018 provided a proof of the Probability Postulate based on symmetry considerations in the framework of the self-location uncertainty of Vaidman 1998. However Kent 2015 and McQueen and Vaidman 2019 argued that their proof fails because it starts with a meaningless question. The proof considers a situation as in a sleeping pill experiment presented above: I was asleep during a quantum measurement, but unlike the original proposal, there was not any change in my state. I was not moved to different rooms according to the results of the experiment. Still, the question is asked: What is the probability for me to be in a world with a particular outcome? Whether that question can be meaningfully asked depends on whether I have branched. The critics argue that, although there are separate worlds, I have not yet branched and thus the question is not meaningful (at this stage, I am in both worlds). The Sebens and Carroll proof might get off the ground if the program of diverging worlds (Saunders 2010, forthcoming-b) succeeds. Note also that Dawid and Friederich 2020 criticise Sebens and Carroll 2018 on other grounds.

Vaidman 2012 uses symmetry to derive the Probability Postulate in another way. He starts from a situation which is symmetric in all relevant respects, so all outcomes must have equal probability. To derive the postulate, he assumes relativistic causality which tells us that the probability of an outcome of a measurement in one location cannot be affected by spatially remote manipulations, see McQueen and Vaidman 2019. Vaidman 2020 stresses, however, that relativistic causality of the evolution of the wave function of the Universe is not enough.

In addition, we have to postulate the relativistic causality of the subjective experience of an observer within his world.

5. Tests of the MWI

It has frequently been claimed, e.g. by De Witt 1970, that the MWI is in principle indistinguishable from the ideal collapse theory. This is not so. The collapse leads to effects that do not exist if the MWI is the correct theory. To observe the collapse we would need a super technology which allows for the “undoing” of a quantum experiment, including a reversal of the detection process by macroscopic devices. See Lockwood 1989 (p. 223), Vaidman 1998 (p. 257), and other proposals in Deutsch 1986. These proposals are all for gedanken experiments that cannot be performed with current or any foreseeable future technology. Indeed, in these experiments an interference of different worlds has to be observed. Worlds are different when at least one macroscopic object is in macroscopically distinguishable states. Thus, what is needed is an interference experiment with a macroscopic body. Today there are interference experiments with larger and larger objects (e.g., molecules with 2000 atoms, see Fein *et al.* 2019), but these objects are still not large enough to be considered “macroscopic”. Such experiments can only refine the constraints on the boundary where the collapse might take place. A decisive experiment should involve the interference of states which differ in a macroscopic number of degrees of freedom: an impossible task for today’s technology. It can be argued, see for example Parrochia 2020, that the burden of an experimental proof lies with the opponents of the MWI, because it is they who claim that there is a new physics beyond the well-tested Schrödinger equation. As the analysis of Schlosshauer 2006 shows, we have no such evidence.

The MWI is wrong if there is a physical process of collapse of the wave function of the Universe to a single-world quantum state. Some ingenious proposals for such a process have been made (see Pearle 1986 and the entry on [collapse theories](#)). These proposals (and Weissman’s 1999 non-linear decoherence idea) have additional observable effects, such as a tiny energy non-conservation, that were tested in several experiments, e.g. Collett *et al.* 1995, Diosi 2015. The effects were not found and some (but not all!) of these models have been ruled out, see Vinante *et al.* 2020.

Much of the experimental evidence for quantum mechanics is statistical in nature. Greaves and Myrvold 2010 argued that our experimental data from quantum experiments supports the Probability Postulate of the MWI no less than it supports the Born rule in other approaches to quantum mechanics (see, however, Kent 2010, Albert 2010, and Price 2010 for some criticisms). Barrett and Huttegger 2020 argue that “even an ideal observer under ideal epistemic conditions may never have any empirical evidence whatsoever for believing that the results of one’s quantum-mechanical experiments are randomly determined”. Thus, statistical analysis of quantum experiments should not help us testing the MWI, but we might mention speculative cosmological arguments in support of the MWI by Page 1999, Kragh 2009, Aguirre and Tegmark 2011, and Tipler 2012.

6. Objections to the MWI

Some of the objections to the MWI follow from misinterpretations due to the multitude of various MWIs. The terminology of the MWI can be confusing: “world” is “universe” in Deutsch 1996, while “universe” is “multiverse”. There are two very different approaches with the same name “The Many-Minds Interpretation (MMI)”. The MMI of Albert and Loewer 1988 mentioned above should not be confused with the MMI of Lockwood *et al.* 1996 (which resembles the approach of Zeh 1981). Further, the MWI in the Heisenberg representation, Deutsch 2002, differs significantly from the MWI presented in the Schrödinger representation (used here). The MWI presented here is very close to Everett’s original proposal, but in the entry on [Everett’s relative state formulation of quantum mechanics](#), as well as in his book, Barrett 1999, uses the name “MWI” for the splitting worlds view publicized by De Witt 1970. This approach has been justly criticized: it has both some kind of collapse (an irreversible splitting of worlds in a preferred basis) and the multitude of worlds. Now we consider some objections in detail.

6.1 Ockham’s Razor

It seems that the preponderance of opposition to the MWI comes from the introduction of a very large number of worlds that we do not see: this looks like an extreme violation of Ockham’s principle: “Entities are not to be multiplied beyond necessity”. However, in judging physical theories one could reasonably argue that one should not multiply physical laws beyond necessity either (such a version of Ockham’s Razor has been applied in the past), and in this respect the MWI is the most economical theory. Indeed, it has all the laws of the standard quantum theory, but without the collapse postulate, which is the most problematic of the physical laws. The MWI is also more economical than Bohmian mechanics, which has in addition the ontology of the particle trajectories and the laws which give their evolution. Tipler 1986a (p. 208) has presented an effective analogy with the criticism of Copernican theory on the grounds of Ockham’s razor.

One might also consider a possible philosophical advantage of the plurality of worlds in the MWI, similar to that claimed by realists about possible worlds, such as Lewis 1986 (see the discussion of the analogy between the MWI and Lewis’s theory by Skyrms 1976 and Wilson 2020). However, the analogy is not complete: Lewis’ theory considers all logically possible worlds, far more than all the worlds that are incorporated in the quantum state of the Universe.

6.2 The Problem of Preferred Basis

A common criticism of the MWI stems from the fact that the formalism of quantum theory allows infinitely many ways to decompose the quantum state of the Universe into a superposition of orthogonal states. The question arises: “Why choose the particular decomposition (2) and not any other?” Since other decompositions might lead to a very different picture, the whole construction seems to lack predictive power.

The locality of physical interactions defines the preferred basis. As described in Section 3.5, only localized states of macroscopic objects are stable. And indeed, due to the extensive research on decoherence, the problem of preferred basis is not considered as a serious objection anymore, see Wallace 2010a. Singling out position as a preferred variable for solving the preferred basis problem might be considered as a weakness, but on the other hand, it is implausible that out of a mathematical theory of vectors in Hilbert space one can derive what our world should be. We have to add some ingredients to our theory and adding locality, the property of all known physical interactions, seems to be very natural (in fact, it plays a crucial role in all interpretations). Hemmo and Shenker 2020 also argued that something has to be added to the Hilbert space structure, but viewed the addition of a locality of interaction postulate as the reason that Ockham’s razor does not cut in favour of the MWI. Note, that taking position as a preferred variable is not an ontological claim here, in contrast to the options discussed in the next section.

6.3 The Wave Function is not Enough

As mentioned above, the gap between the mathematical formalism of the MWI, namely the wave function of the Universe, and our experience is larger than in other interpretations. This is the reason why many thought that the ontology of the wave function is not enough. Bell 1987 (p.201) felt that either the wave function is not everything, or it is not right. He was looking for a theory with local “beables”. Many followed Bell in search of a “primitive ontology” in 3+1 space-time, see Allori *et al.* 2014.

A particular reason why the wave function of the Universe cannot be the whole ontology lies in the argument, led by Maudlin 2010, that this is the wrong type of object. The wave function of the Universe (considered to have N particles) is defined in $3N$ dimensional configuration space, while we need an entity in 3+1 space-time (like the primitive ontology), see discussion by Albert 1996, Lewis 2004, Monton 2006, Ney 2021. Addition of “primitive ontology” to the wave function of the Universe helps us understand our experience, but complicates the mathematical part of the theory. In the framework of the MWI, it is not necessary. The expectation values of the density of each particle in space-time, which is the concept derived from the wave functions corresponding to different worlds, can play the role of “primitive ontology”.

Since interactions between particles are local in space, this is what is needed for finding causal connections ending at our experience. The density of particles is gauge independent and also properly transforms between different Lorentz observers such that they all agree upon their experiences. In particular, the explanation of our experience is unaffected by the “narratability failure” problem of Albert 2013: the wave function description might be different for different Lorentz frames, but the description in terms of densities of particles is the same. Note also an alternative approach based on 3+1 space-time by Wallace and Timpson 2010 who, being dissatisfied with the wave function ontology, introduced the formulation of *Spacetime State Realism*. Recently more works appeared on this subject: Ney and Albert 2013, Myrvold 2015, Gao 2017, Lombardi *et al.* 2019, Maudlin 2019, Chen 2019, Carroll and Singh 2019. These works show significant difficulties in obtaining our world as emergent from the Universal wave function. This explains the skeptical tone of [Everett’s](#)

relative-state formulation of quantum mechanics. But, as discussed in Sec.3, the success of the “emergence” program is not crucial: it is enough to find the counterpart of the world we experience in the Universal wave function.

6.4 Derivation of the Probability Postulate

A popular criticism of the MWI in the past, see Belinfante 1975, which was repeated by Putnam 2005, is based on the naive derivation of the probability of an outcome of a quantum experiment as being proportional to the number of worlds with this outcome. Such a derivation leads to the wrong predictions, but accepting the idea of probability being proportional to the measure of existence of a world resolves this problem. Although this involves adding a postulate, we do not complicate the mathematical part (i) of the theory since we do not change the ontology, namely, the wave function. It is a postulate belonging to part (ii), the connection to our experience, and it is a very natural postulate: differences in the mathematical descriptions of worlds are manifest in our experience, see Saunders 1998.

Another criticism related to probability follows from the claim, apparently made by Everett himself and later by many other proponents of the MWI, see De Witt 1970, that the Probability Postulate can be *derived* just from the formalism of the MWI. Unfortunately, the criticism of this derivation (which might well be correct) is considered to be a criticism of the MWI, see Kent 1990. The recent revival of this claim involving decision theory, Deutsch 1999, 2012, and some other symmetry arguments Zurek 2005, Sebens and Carroll 2018 also encountered strong criticisms (see Section 4.3) which might be perceived as criticisms of the MWI itself. Whereas the MWI may have no advantage over other interpretations insofar as the derivation of the Born rule is concerned, Papineau 2010 argues that it also has no disadvantages.

The issue, named by Wallace 2003 as the “incoherence” probability problem, is arguably the most serious difficulty. How can one talk about probability when all possible outcomes happen? This led Saunders and Wallace 2008a to introduce uncertainty to the MWI, see recent analysis in Saunders forthcoming-b. However, Section 4.2 shows how one can explain the illusion of probability of an observer in a world, while the Universe incorporating all the worlds remains deterministic, see also Vaidman 2014. Albert 2010, 2015 argue that Vaidman’s probability appears too late. Vaidman 2012 and McQueen and Vaidman 2019 answer Albert by viewing the probability as the value of a rational bet on a particular result. The results of the betting of the experimenter are relevant for his successors emerging in different worlds after performing the experiment. Since the experimenter is related to all of his successors and they all have identical rational strategies for betting, then this should also be the strategy of the experimenter before the experiment.

6.5 Social Behavior of a Believer in the MWI

There are claims that a believer in the MWI will behave in an irrational way. One claim is based on the naive argument described in the previous section: a believer who assigns equal probabilities to all different worlds will make equal bets for the outcomes of quantum experiments that have unequal probabilities.

Another claim, Lewis 2000, is related to the strategy of a believer in the MWI who is offered to play a *quantum Russian roulette* game. The argument is that I, who would not accept an offer to play a classical Russian roulette game, should agree to play the roulette any number of times if the triggering occurs according to the outcome of a quantum experiment. Indeed, at the end, there will be one world in which Lev is a multi-millionaire and in all other worlds there will be no Lev Vaidman alive. Thus, in the future, Lev will be a rich and presumably happy man.

However, adopting the Probability Postulate leads all believers in the MWI to behave according to the Behavior Principle and with this principle our behavior is similar to the behavior of a believer in the collapse theory who cares about possible future worlds according to the probability of their occurrence. I should not agree to play quantum Russian roulette because the measure of existence of worlds with Lev dead will be much larger than the measure of existence of the worlds with a rich and alive Lev. This approach also resolves the puzzle which Wilson 2017 raises concerning *The Quantum Doomsday Argument*.

Although in most situations the Behavior Principle makes the MWI believer act in the usual way, there are some situations in which a belief in the MWI might cause a change in behaviour. Assume that I am forced to play a game of Russian roulette and given a choice between classical or quantum roulette. If my subjective preference is to ensure the existence of Lev in the future, I should choose a quantum version. However, if I am terribly afraid of dying, I should choose classical roulette which gives me some chance not to die.

Albrecht and Phillips 2014 claim that even a toss of a regular coin splits the world, so there is no need for a quantum splitter, supporting a common view that the splitting of worlds happens very often. Surely, there are many splitting events: every Geiger counter or single-photon detector splits the world, but the frequency of splitting outside a physics laboratory is a complicated physics question. Not every situation leads to a multitude of worlds: this would contradict our ability to predict how our world will look in the near future.

7. Why the MWI?

For proponents of the MWI, the main reason for adopting it is that it avoids the collapse of the quantum wave. (Other no-collapse theories are not better than MWI for various reasons, e.g., the nonlocality of Bohmian mechanics, see Brown and Wallace 2005; and the disadvantage of all of them is that they have some additional structure, see Vaidman 2014). The collapse postulate is a physical law that differs from all known physics in two aspects: it is genuinely random and it involves some kind of action at a distance. Note that action at a distance due to collapse is a controversial issue, see the discussion in Vaidman 2016b and Myrvold 2016. According to the collapse postulate the outcome of a quantum experiment is not determined by the initial conditions of the Universe prior to the experiment: only the probabilities are governed by the initial state. There is no experimental evidence in favor of collapse and against the MWI. We need not assume that Nature plays dice: science has stronger explanatory power. The MWI is a deterministic theory for a physical Universe and it explains why a world appears to be indeterministic for human observers.

The MWI does not have action at a distance. The most celebrated example of nonlocality of quantum mechanics given by [Bell's theorem](#) in the context of the [Einstein-Podolsky-Rosen argument](#) cannot get off the ground in the framework of the MWI because it requires a single outcome of a quantum experiment, see the discussion in Bacciagaluppi 2002, Brown and Timpson 2016. Although the MWI removes the most bothersome aspect of nonlocality, action at a distance, the other aspect of quantum nonlocality, the nonseparability of remote objects manifested in entanglement, is still there. A “world” is a nonlocal concept. This explains why we observe nonlocal correlations in a particular world.

Deutsch 2012 claims to provide an alternative vindication of quantum locality using a quantum information framework. This approach started with Deutsch and Hayden 2000 analyzing the flow of quantum information using the Heisenberg picture. After discussions by Rubin 2001 and Deutsch 2002, Hewitt-Horsman and Vedral 2007 analyzed the uniqueness of the physical picture of the information flow. Timpson 2005 and Wallace and Timpson 2007 questioned the locality demonstration in this approach and the meaning of the locality claim was clarified in Deutsch 2012. Rubin 2011 suggested that this approach might provide a simpler route toward generalization of the MWI of quantum mechanics to the MWI of field theory. Recent works Raymond-Robichaud 2020, Kuypers and Deutsch 2021, Bédard 2021a, clarified the meaning of the Deutsch and Hayden proposal as an alternative local MWI which not only lacks action at a distance, but provides a set of local descriptions which completely describes the whole physical Universe. However, there is a complexity price. Bédard 2021b argues that *“the descriptor of a single qubit has larger dimensionality than the Schrödinger state of the whole network or of the Universe!”*

The MWI resolves most, if not all, paradoxes of quantum mechanics (e.g., Schrödinger's cat), see Vaidman 1994, McQueen and Vaidman 2020. A physical paradox is a phenomenon contradicting our intuition. The laws of physics govern the Universe incorporating all the worlds and this is why, when we limit ourselves to a single world, we may run into a paradox. An example is getting information about a region from where no particle ever came using the *interaction-free measurement* of Elitzur and Vaidman 1993. Indeed, on the scale of the Universe there is no paradox: in other worlds particles were in that region.

Vaidman 2001 finds it advantageous to think about all worlds together even in analysing a controversial issue of classical probability theory, the [Sleeping Beauty problem](#). Accepting the Probability Postulate reduces the analysis of probability to a calculation of the measures of existence of various worlds. Note, however, that the Quantum Sleeping Beauty problem also became a topic of a hot controversy: Lewis 2007, Papineau and Durà-Vilà 2009, Groisman *et al.* 2013, Bradley 2011, Wilson 2014, Schwarz 2015.

Strong proponents of the MWI can be found among cosmologists, e.g., Tipler 1986b, Aguirre and Tegmark 2011. In quantum cosmology the MWI allows for discussion of the whole Universe, thereby avoiding the difficulty of the standard interpretation which requires an external observer, see Susskind 2016 for more analysis of the connections between the MWI and cosmology. Bousso and Susskind 2012 argued that even considerations in the framework of string theory lead to the MWI.

Another community where many favor the MWI is that of the researchers in quantum information. In quantum computing, the key issue is the parallel processing performed on the same computer; this is very similar to the basic picture of the MWI. Recently the usefulness of the MWI for explaining the speedup of quantum computation has been questioned: Steane 2003, Duwell 2007, Cuffaro 2012, forthcoming. It is not that the quantum computation cannot be understood without the framework of the MWI; rather, it is just easier to think about quantum algorithms as parallel computations performed in parallel worlds, Deutsch and Jozsa 1992. There is no way to use all the information obtained in all parallel computations — the quantum computer algorithm is a method in which the outcomes of all calculations interfere, yielding the desired result. The cluster-state quantum computer also performs parallel computations, although it is harder to see how we get the final result. The criticism follows from identifying the computational worlds with decoherent worlds. A quantum computing process has no decoherence and the preferred basis is chosen to be the computational basis.

Recent studies suggest that some of the fathers of quantum mechanics held views close to the MWI: Allori *et al.* 2011 say this about Schrödinger, and Becker 2004 about von Neumann. At the birth of the MWI Wheeler 1957 wrote: “No escape seems possible from this relative state formulation if one wants to have a complete mathematical model for the quantum mechanics ...” Since then, the MWI struggled against the [Copenhagen interpretation of quantum mechanics](#), see Byrne 2010, Barrett and Byrne 2012, gaining legitimacy in recent years Deutsch 1996, Bevers 2011, Barrett 2011, Tegmark 2014, Susskind 2016, Zurek 2018 and Brown 2020 in spite of the very diverse opinions in the talks of its 50th anniversary celebration: Oxford 2007, Perimeter 2007, Saunders *et al.* 2010.

Berenstein 2020 argues that the MWI is the latest example of successive scientific revolutions which forced humans to abandon the prejudice that they occupy a privileged position at the center of the Universe. The heliocentric model of the Solar System, Darwinian evolution and the Special Theory of Relativity follow this pattern. The MWI offers metaphysical neutrality between the perspectives of observers on different branches of the Universal wave function, as opposed to single-world theories which give a privileged perspective on reality to one observer.

What Is Quantum Computing And Why Is It So Hard To Explain?

You've probably heard the term "[quantum computing](#)" at some point and wondered what it meant. It's not a term that's easy to understand, and neither is quantum mechanics, which is the theory behind the concept of quantum computers. The term "quantum" is thrown around a lot these days, and they even made a running joke of it in "Ant-Man and the Wasp," where Ant-Man asked, "Do you guys just put the word 'quantum' in front of everything?"

It was a fair question because that movie and many others toss around the word "quantum" like a magical explanation for technology a layperson cannot understand. This can seem true in real life because for anyone who doesn't understand quantum mechanics, hearing the word "quantum" to describe computers sounds odd. Quantum computing isn't a simple concept, and while some people understand its potential, it's not something a layperson can't grasp.

If you count yourself among the masses who don't understand quantum computing, you're in luck. This article delves into the concepts surrounding quantum computing and explains them as simply as possible. Of course, it's not a simple theory, but once it's broken down, it's a little easier to understand. That's not to say it isn't incredibly complex and based on detailed scientific theories, but if you have a basic understanding of computing, understanding quantum computing shouldn't be too difficult to grasp.

What Quantum Means In Regards To Computers

The term "quantum computing" is a multidisciplinary field centered around making computers that function differently from standard binary computer systems. Computers, your phone, and most electronic devices function based on a binary, base-2 system, where the number one is the electrical signal for "on" and a zero is the electrical signal for "off." These are called bits, and eight of them make up a byte. Binary computing gives us the Internet, self-driving cars, and much more.

Quantum computing is different because instead of a binary system, it functions using four principles of quantum physics. Don't worry; you don't need to understand quantum physics to understand how this works. The four principles are Superposition, Interference, Entanglement, and Measurement. Superposition allows for a quantum state to be both on and off at the same time, while Interference allows for an object to cross its own path and interfere with another particle.

Interference essentially allows for a particle to not cancel out the other particle, or they can be added to one another. Entanglement is where it gets tricky because it

allows for an object's state to be entangled with another, and neither can be described without also describing the other. Finally, Measurement states that measuring an object forces it to turn into a classical state, so the act of measuring alters the state of an object. What this all means is that using the principles of Quantum Superposition, a bit, or "qubit," can be both a zero and a one at the same time.

How Does This Apply To Computing?

What this all means is that computers using binary systems can create complex systems and analyses, but they're limited by several physical factors. Quantum computing utilizes [quantum physics](#) to create incredibly complex systems, much faster than standard computers. Theoretically, a fully functioning quantum computer could break the most complex cryptographic encryption in a short time, while the most advanced binary supercomputer could take exponentially longer, or it wouldn't be able to complete the operation at all.

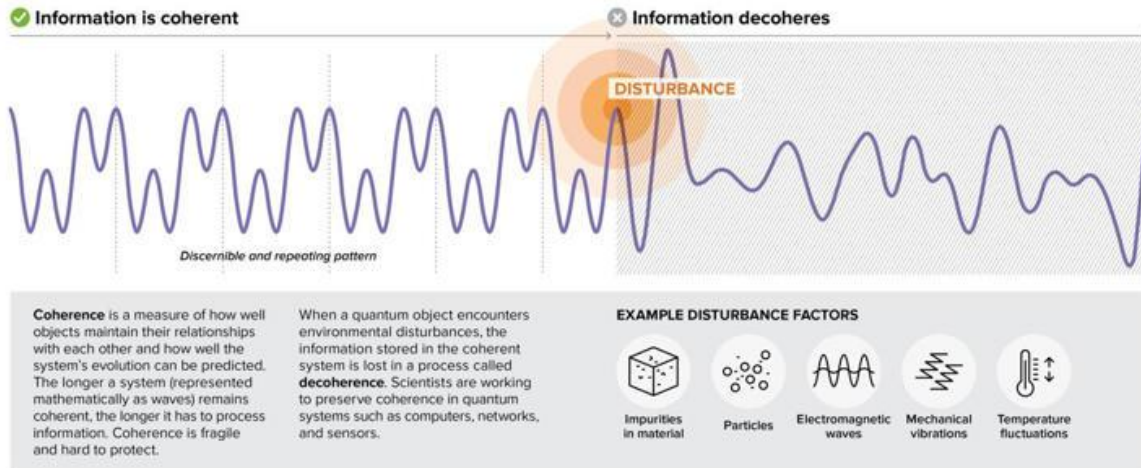
Currently, there are no fully functioning quantum computers capable of performing more efficiently, faster, or cheaper than their binary counterparts, but they are in development by several nations and corporations. [Creating a quantum computer](#) is no easy task, and they require several components: a quantum data plane, which includes the physical qubits and the hardware needed to hold them in place. The control and measurement plane converts digital signals into usable analog or wave control signals capable of performing quantum operations.

The control processor plane and host processor are what utilize the quantum algorithm alongside quantum software to provide a digital signal or bits to the control and measurement plane. Those are the main components, and there's plenty more, but the most important thing to know for quantum computing is that quantum computers use quantum physics to perform functions at a faster rate than current binary computer systems. Essentially, quantum computing is the next step in computer development that will move beyond what is currently technologically possible.

What is quantum coherence?

QUANTUM COHERENCE

Preserving coherence in quantum systems is crucial for quantum computing, communication, and sensing



What is quantum coherence? Credit: Argonne National Laboratory

We say a message is incoherent when we can't make it out, or when it doesn't make sense. A scribbled note, a drunken argument or a conversation taking place five tables down in a crowded cafe might all be incoherent. In general, "coherent" means the opposite—consistent, connected, clear.

In science, the word coherence takes on more specific, mathematical definitions, but they all get at a similar concept: Something is coherent if it can be understood, if it forms a unified whole and if those first two qualities persist.

Scientists originally developed the concept of coherence to understand and describe the wave-like behavior of light. Since then, the concept has been generalized to other systems involving waves, such as acoustic, electronic and quantum mechanical systems.

"Coherence is a measure of how well certain systems will maintain their relationships with each other and how well we are able to predict the evolution of those systems," said Martin Holt, a scientist at the U.S. Department of Energy's (DOE) Argonne National Laboratory and a member of Q-NEXT, a DOE National Quantum Information Science Research Center led by Argonne. "Understanding

and controlling coherence in quantum technologies is crucial because the relationships involved need to be very long-lived and well-understood."

Like researchers around the globe, Q-NEXT scientists are studying and improving coherence in quantum systems for technologies such as quantum sensing and quantum computing. Once realized, these technologies will leverage coherence to perform complex calculations, take high-resolution measurements and transmit unhackable messages, potentially revolutionizing our approach to communication, cybersecurity, simulation, optimization and more.

Coherent waves

Imagine a wave, rising and falling periodically at a certain speed (frequency), and with a certain height or intensity (amplitude). Now, throw in a second wave. If the two waves are offset from each other—if they are not rising and falling together—they are said to be out of phase. It's this phase difference that determines whether the waves will interfere to have an amplifying or canceling effect on each other, or something in between.

We see this in everyday life. Constructive interference occurs when two singers amplify each other's voices, or when you double bounce a friend on the trampoline. Destructive interference of sound waves is the principle behind noise-cancelling headphones.

Two waves are coherent when there is a meaningful relationship between their phases or when their interference creates a well-understood pattern. In essence, coherence is a measure of how in sync the waves are with each other. There are degrees of coherence; waves can be more or less coherent with each other.

Lasers, for example, are designed to emit highly coherent light. They contain atoms that are excited with energy, and upon their decay, emit photons (particles of light) with the same frequency and phase as each other. These photons bounce off mirrors within the laser, which serve to amplify the light traveling only in a certain direction and with a certain frequency. This special interference—or coherence—between photons results in a highly focused and uniform beam of light. Sound waves can be similarly coherent, and scientists have even created sound lasers, or sasers.

Quantum coherence

In quantum mechanics, objects can be represented as either a combination of waves or particles. In principle, this applies to any object. But this way of looking at things works best when dealing with objects that are very small, like photons, other elementary particles and atoms.

Quantum objects can be described with a special type of identifier called a wavefunction. It's sort of a wave on steroids, since it can contain an incredible amount of information within its mathematical nooks and crannies.

This is because wavefunctions are composites of waves themselves. Quantum coherence refers to the phase relationships between these waves—the ones that together describe the whole object. When these waves interfere in coherent ways, it gives rise to quantum superposition, a central feature of quantum mechanics that allows an object to exist in multiple states simultaneously.

Here's where it gets uniquely quantum. The waves composing an object's quantum wavefunction don't correspond to physical values, like position or energy. Instead, they correspond to the likelihood of different possible ways that the state of the object could evolve—for example, the likelihood that its energy will change over time in a certain way, or the likelihood that it will spin a certain way in a certain location. Quantum coherence is an interference between these different possible future histories of the object.

However, this interference can exist only until the system is observed or disturbed. At that point, the interference between the waves vanishes, and the superposition is lost. The object has apparently experienced only one of the possible histories.

What does it mean for possible future histories to interfere? And for the wavefunction to collapse into just one of those histories? Those are tough questions. Currently, we know more about how to use this feature of quantum mechanics than what it means for the nature of our reality.

Sensing at the quantum level

Coherence is fragile and hard to protect. Perfectly isolated quantum objects and systems can maintain coherence indefinitely, but it would be impossible to manipulate or investigate them.

As a quantum object encounters other objects or fields, it picks up random influences from each. Even the act of measuring the object necessarily introduces noise, rendering its original wavefunction difficult—if not impossible—to decipher. As a result, the information that was stored in the coherent system is lost in a process called decoherence.

But for some applications, decoherence can be an advantage.

"If you prepare an object in a certain superposition of states with a certain coherence, and you send it into an environment with unknown influences, then a change in the object's phase relationship can provide meaningful information about the environment," said Jennifer Dionne, a professor of materials science and radiology at Stanford University and deputy director of Q-NEXT.

Here, the quantum object itself is the sensor. Because its phase relationship is so sensitive, it responds to subtle influences from the environment in a big way. This sensitivity could enable extremely high-resolution detection and imaging. Quantum coherence allows scientists to start off the sensor in a well-understood state that will persist over time. This makes it easier to retroactively determine how that state changed and what those changes mean about the environment.

For example, Dionne's lab is developing quantum sensors to detect force.

"We are studying how the colors of nanoparticles change when they encounter mechanical force within an organism," Dionne said. "We've started to deploy these sensors in living organisms using worms as test subjects. As the worms' digestive tracts apply force, quantum transitions within the nanoparticle cause it to change color, which we can read out during digestion."

Atomic clocks and gravitational wave sensors also rely on quantum coherence for ultraprecision. Other examples of future sensing applications using quantum coherence include miniaturized magnetic resonance imaging (MRI) technologies, which could be used to scan single cells or molecules or significantly improve the resolution of whole-organism MRI scans.

Quantum coherence plays a role in biological systems, too. Scientists believe that birds use quantum coherence of proteins in their eyes to sense Earth's magnetic field for navigation, like an internal GPS. Researchers are developing magnetic field sensors using the same principles to help humans navigate in situations where satellite-based GPS is impossible.

Wave hello to quantum computing

One coherent object can serve as a great sensor. Two or more quantum objects that are coherent with each other enable quantum computation.

The traditional, or classical, bit in a computer can exist in one of two states, 0 or 1. Thanks to quantum superposition, a quantum bit—a qubit—can exist in a combination of the two states simultaneously. Coherence is responsible for maintaining the phase relationships, and therefore the superposition, between these states over time and space.

"In quantum computing, instead of doing operations such as addition or multiplication on classical bits, you're performing operations on different components of the waves that make up the wavefunction," Dionne said. "It's important to maintain coherence long enough so that as the computer performs operations, it isn't accumulating errors as the different parts of the wavefunction decohere."

Coherence is also responsible for maintaining entanglement, a special case of superposition that is crucial for quantum computing. When quantum objects are entangled, they maintain a particular correlation with each other even if they are physically separated by large distances.

"As long as two entangled objects remain coherent with each other, you can perform an operation on one of them, and that will give you information about the other," Dionne said.

Say you want to use a quantum computer to predict the success of a pizza party you plan to throw. First, you need to decide what factors would contribute to a successful party, such as the taste of the pizza and the number of guests. You might assign one qubit to represent the ratio of water to flour in your pizza dough, with 0 representing no water, 1 representing only water and the

superposition between them representing all possible ratios. Another qubit could represent the number of people that show up, ranging from no one to everyone you invited. Perhaps a third qubit represents how likely you are to burn your food, and so on.

"You have all of these probabilities captured in clean, coherent states, and you let the system evolve over time," Holt said. "If you repeat the simulation enough, you get the probability of how successful the party will be based on the factors you encoded in the wavefunctions of the entangled qubits. But the simulation keeps going only if the states are coherent."

Because of the way information is embedded in the wavefunction, just a small number of qubits can represent very complicated, real-world problems with lots of dependencies, such as power grid optimization or finding the most energy-efficient way to distribute goods across the globe. The longer the system is coherent, the more complex the calculations can be.

Preserving quantum coherence

Holt's work at Argonne focuses on the development of matter-based qubits, where a defect—a replaced atom or an atomic vacancy, for instance—is embedded in a material's otherwise normal structure. Although scientists try to protect the defects from decoherence, small changes in temperature, pressure or magnetic fields can introduce noise.

Imagine you're running at the gym, and music is playing over the speakers. You notice it's difficult to run at your own pace rather than running to the beat of the music, and it's ruining your flow.

"There are a couple of ways to prevent this," Holt said. "You could wear earplugs so that you're isolated from the external influence, or you could start running significantly faster or slower so that it's easier to decouple your body's rhythm from that of the music. Then, even if the music changes, you don't care because you're just that far off from it."

To isolate qubits from noise, scientists keep quantum computers very cold—near absolute zero. They further decouple the qubits from their surroundings by

designing and manipulating the states of the qubits to respond to frequencies of light or sound that their surroundings aren't affected by.

This is difficult to achieve, and different types of qubits are easier to protect than others. So far, the longest-lived qubits are called trapped atoms, which have been shown to remain coherent for several minutes or more. However, these qubits are difficult to use for computing applications. A recent demonstration of long-lived coherence was made by Q-NEXT scientists at Argonne and the University of Chicago. The team showed that a certain semiconductor qubit—a type of qubit that is more promising for quantum computing—stayed coherent for over five seconds.

"Preventing the loss of information through decoherence is the hard part of quantum information science, and that's why the field is called that," Holt said. "It's not just quantum science, it's information processing using quantum coherence."

Provided by Argonne National Laboratory

FEBRUARY 17, 2025

Researchers spin 'wheel of fortune' to find a fundamental proof of quantum mechanics

by [National University of Singapore](#)

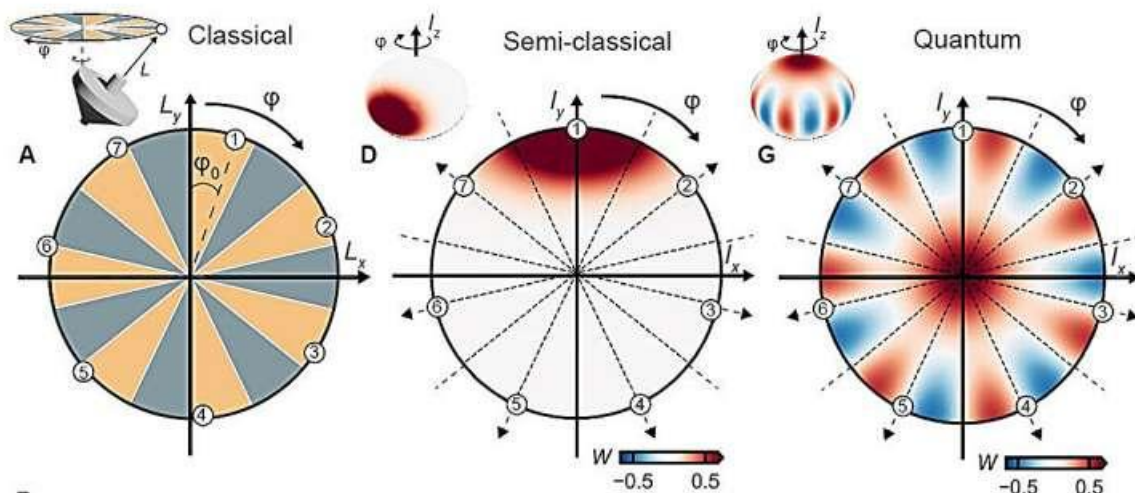


Diagram illustrating the quantum spin proof provided by teams from NUS and UNSW in the journal *Newton*. The left panel shows a classical 'Wheel of Fortune' where the maximum of each shaded panel on either side can never be more than four. The middle panel shows the quantum-blurred probability of finding a spin pointing in a certain direction. On the right is the probability function of a striking nonclassical, 'Schrödinger cat' state, where the spin is in a superposition of pointing in opposite directions. This spin returns a probability of being positive equal to 0.636, which is larger than the classical maximum of 0.571, thus proving that the spin is in a state that cannot be described by classical physics.

Credit: *Newton* (2025). DOI: 10.1016/j.newton.2025.100017

Researchers from the National University of Singapore (NUS) and University of New South Wales (UNSW) Sydney have proven that a spinning atomic nucleus really is fundamentally a quantum resource. The teams were led respectively by Professor Valerio Scarani, from NUS Department of Physics, and Scientia Professor Andrea Morello from UNSW Engineering. The paper was [published](#) in the journal *Newton* on 14 February 2025.

It has long been inferred that tiny particles such as electrons or protons are indeed quantum due to the way they get deflected in a magnetic field. However, when left to spin freely, they appear to behave in exactly the same way as a classical spinning item, such as a Wheel of Fortune turning on its axis. For more than half a century, experts in spin resonance have taken this fact as a universal truth.

For the same reason, a technician or a doctor operating a [magnetic resonance imaging](#) (MRI) machine at the hospital never needed to understand quantum mechanics—

the spinning of the protons inside the patient's body produces the same kind of magnetic field that would be created by attaching a fridge magnet to a spinning wheel.

The new work involves a more intricate kind of measurement performed on a [single atom](#) to demonstrate clearly the quantum behavior of spinning nuclei.

Solving the riddle

Prof Scarani, who is also Deputy Director of Singapore's Center for Quantum Technologies (CQT), first proposed the theory after coming across a paper in 2021, written by Russian-Israeli mathematician Boris Tsirelson some 15 years earlier. The paper explored the probability of detecting objects in particular locations as they moved back and forth in a rhythmical way.

As a quantum physicist, Prof Scarani wondered if he could build on that work and utilize it instead in relation to the behavior of single quantum objects as they spin—and particularly to solve the riddle of why such tiny particles seemed to behave no differently from normal, non-quantum objects.

Having worked for some years with his student Zaw Lin Htoo to solve the problem, Prof Scarani set out to test their theory that in certain special states it would be possible to definitively show that an [atomic nucleus](#) does indeed have quantum properties.

A collaboration with Prof Morello from the School of Electrical Engineering and Telecommunications at UNSW provided the skills and the ultra-precise measurement equipment to run the experiments that proved it was true.

"For one particle on its own, nobody thought that you could get any deviation between the classical and the quantum behavior," Prof Scarani said.

"Andrea's group put into motion the spin of a nucleus of antimony, and for every cycle or rotation took seven measurements to check whether it pointed in the positive direction or not. Using the Wheel of Fortune analogy, one would expect to find an arrow on the wheel pointing to the right either 4 out of 7 times, or 3 out of 7 times.

"Classically, the absolute maximum is 4 out of 7—it is inescapable. But the [quantum theory](#) predicted that, in the special state we wanted to create, a higher probability could be observed.

"The deviation between the classical and quantum behavior is quite small, but statistically significant. To notice such deviation, you have to make sure that the measurement is extremely precise and free from noise, otherwise you will not see that difference."

From the UNSW team, Ph.D. student Arjen Vaartjes and Dr. Martin Nurizzo, led the experiment which produced the results to prove the new theory.

Prof Morello took a big thrill out of being able to challenge the long-established textbooks.

"This is fundamental science. Previously it was thought there was no way to ascertain that a nuclear spin is actually a quantum mechanical object by simply watching its precession in a magnetic field. What we have done here is to contradict that.

"We have shown that actually it is possible. Yes, you need to have some special kinds of nuclear spins, and put them in some very peculiar quantum states, and you need a sophisticated way of observing them. The special quantum state we used is called the 'Schrödinger cat state,' and has interesting features of its own.

"But the result is a proof that clarifies what is a quantum resource."

Discover the latest in science, tech, and space with over **100,000 subscribers** who rely on Phys.org for daily insights. Sign up for our [free newsletter](#) and get updates on breakthroughs, innovations, and research that matter—**daily or weekly**.

Subscribe

Observation of the truth

Prof Scarani and Prof Morello are delighted to have made this breakthrough in the understanding of how quantum phenomena manifest themselves in spin precession, regardless of possible applications.

"Within the community of scientists, this experiment will bring these ideas more to the fore," said Prof Scarani.

"The key challenge is that you need to create these very specific states in order to see the effect. That said, those special Schrödinger cat states are likely to be important quantum resources in quantum computing, so what we have done here could become a very efficient method to certify their creation."

With 2025 designated by the United Nations as the International Year of Quantum Science and Technology, marking a century since the initial development of [quantum mechanics](#), Prof Morello is proud to have validated such a fundamental principle.

"Quantum mechanics has been around for 100 years, so you might think we'd have figured it all out, right?" he said. "And yet, in 2025, we can still come up with a really simple but clever idea, which we can test in a real experiment, that makes you rethink what it means to be quantum.

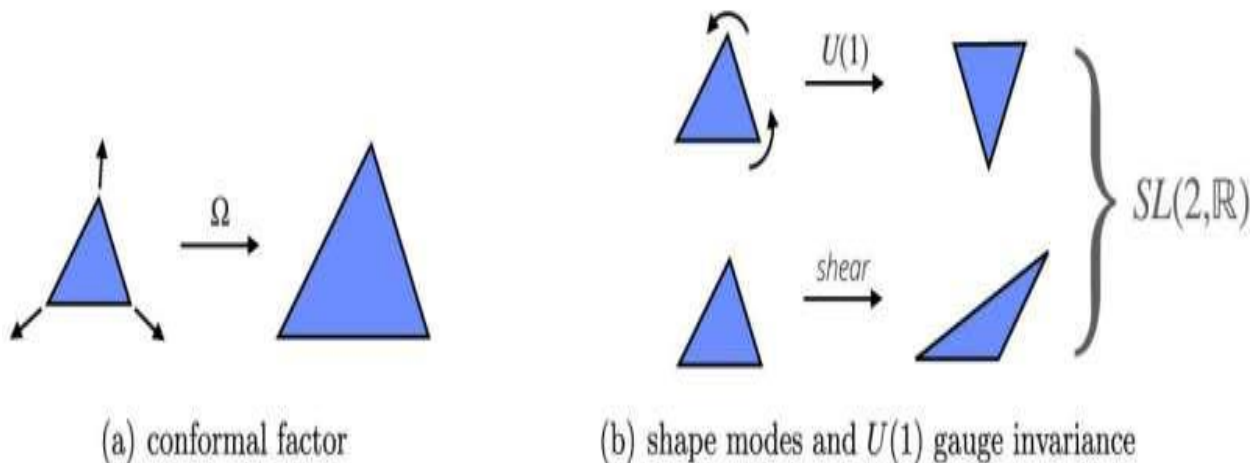
"This is really more of a work of intellectual beauty and intellectual satisfaction than it is an immediate application. It is an observation of the truth."

More information: Arjen Vaartjes et al, Certifying the quantumness of a nuclear spin qudit through its uniform precession, *Newton* (2025). DOI: [10.1016/j.newton.2025.100017](https://doi.org/10.1016/j.newton.2025.100017)
Provided by [National University of Singapore](#)

MARCH 13, 2025

Exploring the limits of power: Where quantum theory and the theory of relativity meet

by Friedrich–Alexander University Erlangen–Nürnberg



A null boundary carries a degenerate signature (0++) metric, which is obtained by taking the pull-back of the four-dimensional line element to the boundary. Credit: *Classical and Quantum Gravity* (2025). DOI: 10.1088/1361-6382/adb536

Physics has a problem—their key models of quantum theory and the theory of relativity do not fit together. Now, Dr. Wolfgang Wieland from Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) is developing an approach that reconciles the two theories in a problematic area. A recently published paper that was [published](#) in *Classical and Quantum Gravity* gives hope that this could work.

There are four [fundamental forces](#) in the universe: gravity, electromagnetism, the weak and the strong interaction. While general relativity describes gravity, [quantum theory](#) deals with the other three forces. This creates a problem: "As early as the 1930s, it was recognized that the two theories do not fit together," explains Dr. Wieland, who leads a Heisenberg project on this topic at the Chair of Quantum Gravity at FAU.

Usually, this has no major consequences: general relativity is mainly used to calculate the behavior of large masses in the universe. Quantum theory, on the other hand, focuses on the world of the very smallest things. However, to better understand key phenomena such as the Big Bang or [black holes](#), a model is needed that unites both concepts—quantum gravity. General relativity states that all matter in a black hole is united at one tiny point. It is

therefore important to understand how gigantic gravitational forces act in the microcosm, although this is where the laws of quantum mechanics actually apply.

Concepts of cause and effect do not apply in black holes

The theory of quantum gravity could turn our concept of causality under extreme conditions on its head: "Time determines the relationship between cause and effect—causes lie in the past, effects in the future," explains Wieland. "This assumption is firmly embedded in [quantum mechanics](#). However, general relativity predicts that large masses bend spacetime due to their gravity. In a black hole, this effect is so extreme that the terms 'before' and 'after' have no meaning. This has enormous implications for our understanding of cause and effect."

For decades, research has been trying to find a theory of [quantum gravity](#) that allows statements to be made under such [extreme conditions](#). One problem is that in quantum theory, energy is divided into the smallest possible packages, the quanta. Observables such as energy or [angular momentum](#) can only take discrete values, not continuous ones. This also affects the electromagnetic, weak, and strong interactions, they are also "quantized."

Gravity cannot be simply broken down into quanta, but since it arises from the curvature of spacetime according to the theory of relativity, a detour could be possible. "Our approach is that space and time themselves are not continuous but consist of small portions," explains Wieland. "If this thesis is correct, then gravity can also be described with the help of quantum theory."

Is spacetime granular?

In a quantized spacetime, we cannot move a cup by any arbitrary distance, only by fixed steps. Likewise, there is no clock that divides the passage of time into arbitrarily fine intervals—it progresses in steps, like the second hand of an analog clock. In the macroscopic world, these steps are not observed because they are extremely small.

An important role in this concept of quantized spacetime is played by the Planck units coined by Max Planck. These are a fundamental system of units that can be constructed solely from the speed of light and the natural constants of gravity and quantum theory. Another constant, the Planck power, can be calculated from the Planck units. Wieland's current publication focuses on the Planck power.

Discover the latest in science, tech, and space with over **100,000 subscribers** who rely on Phys.org for daily insights. Sign up for our [free newsletter](#) and get updates on breakthroughs, innovations, and research that matter—**daily or weekly**.

Subscribe

"Our current understanding is that power—that is, the amount of energy that can be emitted per unit of time—can become infinitely large in our universe," he explains. "This leads to

some of the partial equations in a quantum theoretical description of gravity becoming unsolvable."

In the study, Wieland shows that in a quantized spacetime, there is an upper limit for power. This limit, which, like the speed of light, cannot be exceeded, is the aforementioned Planck power. It is unimaginably large at 10^{53} watts—but still limited.

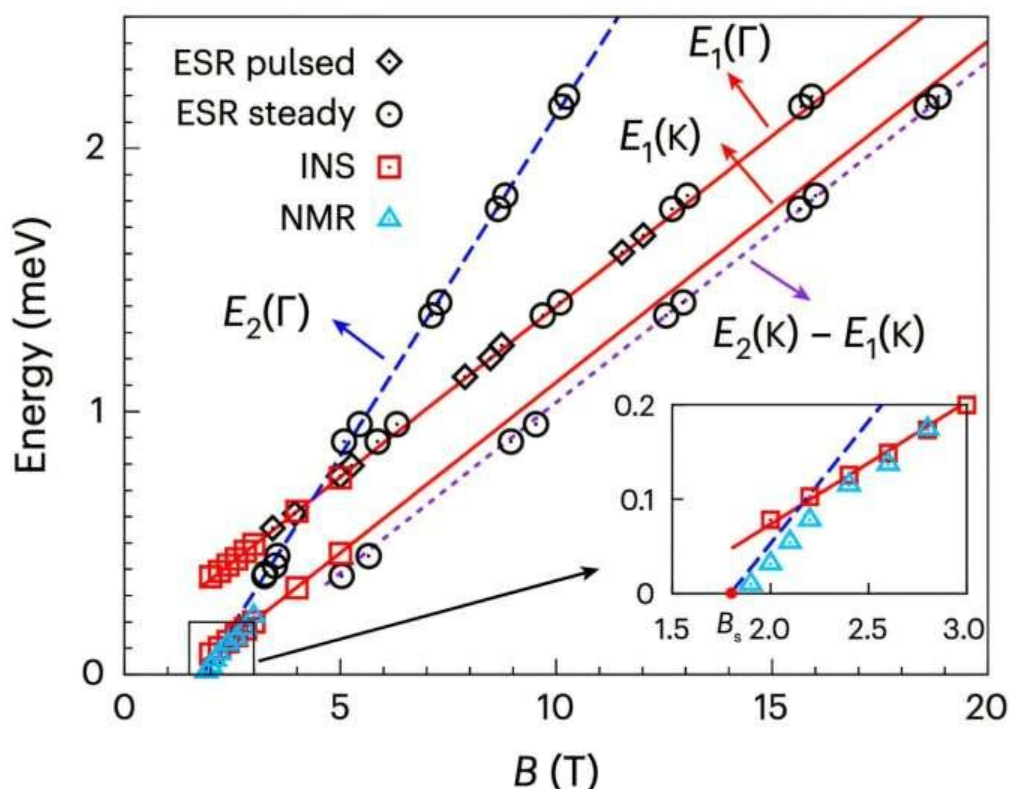
"If my theoretical considerations prove true, it will be possible to break down the power of gravitational waves into the smallest quanta," explains Wieland. In his Heisenberg project, he will not only address this problem but also the question of how gravity influences the causal structure of the world.

More information: Wolfgang Wieland, Evidence for Planck luminosity bound in quantum gravity, *Classical and Quantum Gravity* (2025). DOI: [10.1088/1361-6382/adb536](https://doi.org/10.1088/1361-6382/adb536)
Provided by [Friedrich–Alexander University Erlangen–Nürnberg](https://www.fraunhofer.de/en)

MARCH 13, 2025

First observation of Bose–Einstein condensation of two-magnon bound state in spin-1 triangular lattice reported

by Tong Wei and Zhao Weiwei, [Chinese Academy of Sciences](#)



Calculate the excitation energy of single magnon and two-magnon bound states obtained from theoretical (solid and dashed lines) and experimental measurements (hollow symbols). Credit: SHEN Jieming

Using the Multi-frequency High Field Electron Spin Resonance Spectrometer at the Steady-State High Magnetic Field Facility (SHMFF), researchers observed the first-ever Bose–Einstein condensation (BEC) of a two-magnon bound state in a magnetic material. The facility is in the Hefei Institutes of Physical Science of the Chinese Academy of Sciences and includes a research team from Southern University of Science and Technology, Zhejiang University, Renmin University of China, and the Australian Nuclear Science and Technology Organization.

This discovery was [published](#) in *Nature Materials*.

BEC is a fascinating quantum phenomenon where particles, typically bosons, condense into a single collective state at ultra-low temperatures. While this effect has been seen in cold atoms, it had never been observed in a magnetic system until now.

In this study, the researchers focused on magnons—quanta of spin excitations—and discovered that pairs of magnons could bind together and form a condensed state, similar to BEC in atoms.

The material at the heart of this discovery is $\text{Na}_2\text{BaNi}(\text{PO}_4)_2$, a quantum magnetic compound with a unique triangular lattice structure. This structure makes it a perfect candidate for studying frustrated quantum magnetism—a state where spins of electrons behave in strange, unpredictable ways due to competing interactions.

This discovery differs from conventional superconductivity, which involves pairing fermions. Instead, the team uncovered a unique form of magnon pairing that leads to a [quantum phase transition](#), offering fresh insights into exotic quantum states of matter.

SHMFF allowed them to detect minuscule signals corresponding to two-magnon bound states, which matched theoretical predictions. Their experiments also included low-temperature thermodynamics, neutron scattering, and nuclear magnetic resonance techniques, further confirming the existence of the [magnon BEC](#).

This achievement paves the way for deeper exploration of quantum materials, potentially unlocking new phases of matter that could be harnessed in future technologies, according to the team.

More information: Jieming Sheng et al, Bose–Einstein condensation of a two-magnon bound state in a spin-1 triangular lattice, *Nature Materials* (2025). DOI: [10.1038/s41563-024-02071-z](https://doi.org/10.1038/s41563-024-02071-z)

Journal information: [Nature Materials](#)

Provided by [Chinese Academy of Sciences](#)

Quantum Supremacy: What Is It and Why Do We Want It?

- Quantum supremacy is achieved when a quantum computer can solve problems impractical for classical computers due to time constraints.
- Quantum computers differ in operation, using qubits that can represent a one and a zero simultaneously.
- Achieving quantum supremacy would revolutionize various industries and render current encryption ineffective.

With every passing day, quantum computers are getting closer to being practical computers that can be put to use in various industries and walks of life, but what are scientists and engineers actually aiming for? When will these computers be ready?

One measure is that of "quantum supremacy". Once quantum supremacy is demonstrated, it will usher in the age of quantum computers for real, but what does it mean for quantum computers to have supremacy?

Understanding Quantum Supremacy

In principle, quantum supremacy is something that has to be demonstrated over "classical" computers. That is, the computer you're using right now to read this. It uses binary logic to perform computations. At its core, it's all ones and zeros.

A quantum computer has "quantum supremacy" when it can do a calculation that's impractical for a classical computer to do because it would take too long to be useful. We know from Alan Turing's [Universal Turing Machine](#) that you can compute the answer to anything you can express mathematically with a classical computer. It's just that the answer might take several thousand times as long to compute as the age of the universe!

This is actually a good time to stop and watch this brief explanation of Universal Turing Machines from the Computerphile channel.

It seems counterintuitive that such a simple machine could effectively compute any algorithm, but the math has been checked out by people who are orders of magnitude smarter than I am, so I guess I'll have to take their word for it.

So the core of supremacy is demonstrating that quantum computers can solve certain problems that classical computers can also solve, but can't solve for practical purposes.

How can quantum computers (in theory) seemingly skip all that work and get to the answer so much faster than a classical computer? It all comes down to how these different computer systems work.

A classical computer processes information in the form of binary code. Everything in a computer boils down to data represented in some way as a one or a zero. From these ones and zeros, we can build symbol manipulation codes. For example, if you have eight bits (binary digits) you have 256 possible permutations of ones and zeros. Which means you can represent 256 numbers, which can each stand for something. There are 128 standard ASCII characters represented by a seven-bit binary number. The extended eight-bit ASCII set has 256 characters.

As you increase the bit-length, you exponentially increase the number of values you can represent, which is why a 32-bit computer can only address 4GiB worth of RAM, but a 64-bit computer can address (in theory) 16 Exabytes of the stuff.

This is really useful since you can represent these two states in so many ways, such as magnetic field strengths on tape, pits and lands on a CD, or the levels of electrical charge inside a CPU or the memory cells of an SSD.

Quantum computers fundamentally differ from classical computers. Instead of binary digits called bits, they use quantum digits called "qubits". A qubit makes use of quantum phenomena and can be a one or a zero at the same time. Because every bit is in "superposition" the quantum computer can compute all possible answers at the same time. Then, when you measure the value of the qubits, they collapse into the correct answer.

Yes, I don't really know how it works either.

Nonetheless, based on how they work, and that they've been shown to work, these quantum computers have the potential to compute in seconds what would

take the fastest classical computers in the world millions of years and of the energy in our solar system. So why aren't they supreme already?

Well, for one thing, qubits are incredibly fragile, and the number of them has to be scaled up dramatically for a quantum computer to actually be useful. Existing quantum computers only have a handful of qubits and are good for little more than proving the concept works.

The main thing scientists and engineers are working on is creating robust qubits, figuring out how to cram as many of them into a quantum computer as possible, and perhaps making it all work at room temperature.

Claims of Quantum Supremacy Are Controversial

Google claimed in 2019 that its 53-qubit Sycamore processor had [achieved quantum supremacy](#) by solving a complex problem in 200 seconds—a task they estimated would take the world's most powerful classical supercomputer thousands of years. This was for one specific problem known as "[random circuit sampling](#)" and not general supremacy.

IBM, a leader in both classical and quantum computing, argued that their classical supercomputers could, with clever optimizations, solve the same problem much faster than Google's initial estimates suggested—casting doubt on [whether true supremacy had been reached](#).

It's also interesting that there's been pushback against the term "supremacy", which some academics feel has problematic overtones that needlessly evoke unrelated social issues based on race or ethnicity. Which is why some people prefer to use "quantum advantage" to mean the same thing, but you'll find uses of both terms all over the place.

What Happens When We Achieve Supremacy for Real?

So what happens when quantum computers finally get their act together and can solve problems that take too long and are too expensive for current computers? The truth is that the world will probably change in some profound ways, and that's without taking into account how the recent revolution in AI has already blown the doors off some problems, such as predicting practically every protein structure we can think of.

The big one everyone's likely heard of is that all our current strong encryption will be useless overnight. These encryption algorithms work specifically on the principle that they are fast and cheap to apply using a classical computer, but they'd take thousands or millions of years to crack.

Well, a quantum computer with sufficient qubits could open these virtual locks as if they weren't there. Of course, we've already designed post-quantum encryption methods that are hard even for quantum computers to break, in theory. Still, a lot of data is going to be retroactively cracked open and that could be bad for obvious reasons.

While AI has done a tremendous job accelerating materials science and medical research, quantum computers could amp this up even more, helping us find new medicines and other chemicals quickly.

Speaking of AI, adding some qubits into the mix could truly supercharge the mental states of our best AI today, allowing them to consider a huge number of possibilities almost instantly.

If nothing else, quantum computers will likely be excellent at logistics, making our use of energy and resources much better, and maybe getting rid of traffic jams forever. Now that's a cause I think we can all get behind.

Researchers discover a new type of quantum entanglement



Conversion occurring in a nanometric system of two photons into an entangled state in their total angular momentum. Credit: Shalom Buberan, Shultz3d

A study from Technion unveils a newly discovered form of quantum entanglement in the total angular momentum of photons confined in nanoscale structures. This discovery could play a key role in the future miniaturization of quantum communication and computing components.

Quantum physics sometimes leads to very unconventional predictions. This is what happened when Albert Einstein and his colleagues, Boris Podolsky and Nathan Rosen (who later founded the Faculty of Physics at Technion), found a scenario in which knowing the state of one particle immediately affects the state of the other particle, no matter how great the distance between them. Their historic 1935 paper was nicknamed EPR after its three authors (Einstein–Podolsky–Rosen).

The idea that knowing the state of one particle will affect another particle located at a huge distance from it, without physical interaction and information transfer, seemed absurd to Einstein, who called it "spooky action at a distance."

But groundbreaking work by another Technion researcher, Research Prof. Asher Peres from the Faculty of Physics, showed that this property can be used to transmit information in a hidden way—quantum teleportation, which is the basis for quantum communication. This discovery was made by Prof. Peres with his colleagues Charles Bennett and Gilles Brassard.

The phenomenon later received the scientific name quantum entanglement, and for its measurement and implications, which include the possibility of quantum computing and quantum communication, the 2022 Nobel Prize in Physics was awarded to Profs. Alain Aspect and Anton Zeilinger, who previously received honorary doctorates from the Technion, and their colleague Prof. John Clauser.

Quantum entanglement has been demonstrated so far for a wide variety of particles and for their various properties. For photons, particles of light, entanglement can exist for their direction of travel, frequency (color), or the direction in which their electric field points. It can also exist for properties that are harder to imagine, such as angular momentum.

This property is divided into spin, which is related to the photon's rotation of the electric field, and orbit, which is related to the photon's rotational motion in space. This is intuitively similar to Earth, which rotates on its axis and also orbits the sun in a circular path.

It is easy for us to imagine these two rotational properties as separate quantities, and indeed, photons bound in a beam of light much wider than their wavelength. However, when we try to put photons into structures smaller than the photonic wavelength—which is the endeavor of the field of nanophotonics—we discover that it is impossible to separate the different rotational properties, and the photon is characterized by a single quantity, the total angular momentum.

So why would we even want to put photons into such small structures? There are two main reasons for this. One is obvious—it will help us to miniaturize devices that use light and thus squeeze more operations into a small area cell, similar to the miniaturization of electronic circuits.

The other reason is even more important: this miniaturization increases the interaction between the photon and the material through which the photon is traveling (or is near), thus allowing us to produce phenomena and uses that are not possible with photons in their "normal" dimensions.

In a study [published](#) in the journal *Nature*, the Technion researchers, led by Ph.D. student Amit Kam and Dr. Shai Tseskes, discovered that it is possible to entangle photons in nanoscale systems that are a thousandth the size of a hair, but the entanglement is not carried out by the conventional properties of the photon, such as spin or trajectory, but only by the total angular momentum.

The Technion researchers revealed the process that photons undergo from the stage in which they are introduced into the nanoscale system until they exit the measurement system, and found that this transition enriches the space of states that the photons can reside in.

In a series of measurements, the researchers mapped those states, entangled them with the same property unique to nanoscale systems, and confirmed the correspondence between photon pairs that indicates quantum entanglement.

This is the first discovery of a new quantum entanglement in more than 20 years, and it may lead in the future to the development of new tools for the design of photon-based quantum communication and computing components, as well as to their significant miniaturization.

More information: Amit Kam et al, Near-field photon entanglement in total angular momentum, *Nature* (2025). [DOI: 10.1038/s41586-025-08761-1](https://doi.org/10.1038/s41586-025-08761-1)

Provided by Technion - Israel Institute of Technology

What is quantum coherence?

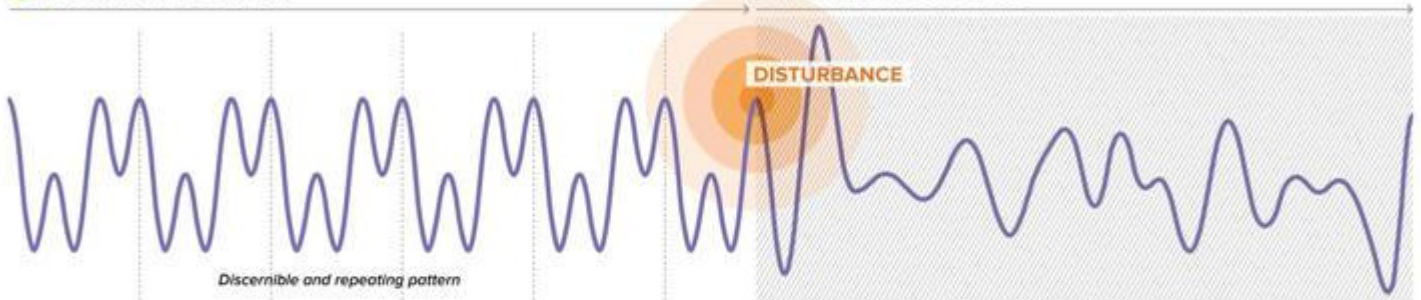
QUANTUM COHERENCE

Preserving coherence in quantum systems is crucial for quantum computing, communication, and sensing



✓ Information is coherent

✗ Information decoheres



Coherence is a measure of how well objects maintain their relationships with each other and how well the system's evolution can be predicted. The longer a system (represented mathematically as waves) remains coherent, the longer it has to process information. Coherence is fragile and hard to protect.

When a quantum object encounters environmental disturbances, the information stored in the coherent system is lost in a process called **decoherence**. Scientists are working to preserve coherence in quantum systems such as computers, networks, and sensors.

EXAMPLE DISTURBANCE FACTORS



Impurities in material



Particles



Electromagnetic waves



Mechanical vibrations



Temperature fluctuations



What is quantum coherence? Credit: Argonne National Laboratory

We say a message is incoherent when we can't make it out, or when it doesn't make sense. A scribbled note, a drunken argument or a conversation taking place five tables down in a crowded cafe might all be incoherent. In general, "coherent" means the opposite—consistent, connected, clear.

In science, the word coherence takes on more specific, mathematical definitions, but they all get at a similar concept: Something is coherent if it can be understood, if it forms a unified whole and if those first two qualities persist.

Scientists originally developed the concept of coherence to understand and describe the wave-like behavior of light. Since then, the concept has been generalized to other systems involving waves, such as acoustic, electronic and quantum mechanical systems.

"Coherence is a measure of how well certain systems will maintain their relationships with each other and how well we are able to predict the evolution of those systems," said Martin Holt, a scientist at the U.S. Department of Energy's (DOE) Argonne National Laboratory and a member of Q-NEXT, a DOE National Quantum Information Science Research Center led by Argonne. "Understanding and controlling coherence in quantum technologies is crucial because the relationships involved need to be very long-lived and well-understood."

Like researchers around the globe, Q-NEXT scientists are studying and improving coherence in quantum systems for technologies such as quantum sensing and quantum computing. Once realized, these technologies will leverage coherence to perform complex calculations, take high-resolution measurements and transmit unhackable messages, potentially revolutionizing our approach to communication, cybersecurity, simulation, optimization and more.

Coherent waves

Imagine a wave, rising and falling periodically at a certain speed (frequency), and with a certain height or intensity (amplitude). Now, throw in a second wave. If the two waves are offset from each other—if they are not rising and falling together—they are said to be out of phase. It's this phase difference that determines whether the waves will interfere to have an amplifying or canceling effect on each other, or something in between.

We see this in everyday life. Constructive interference occurs when two singers amplify each other's voices, or when you double bounce a friend on the trampoline. Destructive interference of sound waves is the principle behind noise-cancelling headphones.

Two waves are coherent when there is a meaningful relationship between their phases or when their interference creates a well-understood pattern. In essence, coherence is a measure of how in sync the waves are with each other. There are degrees of coherence; waves can be more or less coherent with each other.

Lasers, for example, are designed to emit highly coherent light. They contain atoms that are excited with energy, and upon their decay, emit photons (particles

of light) with the same frequency and phase as each other. These photons bounce off mirrors within the laser, which serve to amplify the light traveling only in a certain direction and with a certain frequency. This special interference—or coherence—between photons results in a highly focused and uniform beam of light. Sound waves can be similarly coherent, and scientists have even created sound lasers, or sasers.

Quantum coherence

In quantum mechanics, objects can be represented as either a combination of waves or particles. In principle, this applies to any object. But this way of looking at things works best when dealing with objects that are very small, like photons, other elementary particles and atoms.

Quantum objects can be described with a special type of identifier called a wavefunction. It's sort of a wave on steroids, since it can contain an incredible amount of information within its mathematical nooks and crannies.

This is because wavefunctions are composites of waves themselves. Quantum coherence refers to the phase relationships between these waves—the ones that together describe the whole object. When these waves interfere in coherent ways, it gives rise to quantum superposition, a central feature of quantum mechanics that allows an object to exist in multiple states simultaneously.

Here's where it gets uniquely quantum. The waves composing an object's quantum wavefunction don't correspond to physical values, like position or energy. Instead, they correspond to the likelihood of different possible ways that the state of the object could evolve—for example, the likelihood that its energy will change over time in a certain way, or the likelihood that it will spin a certain way in a certain location. Quantum coherence is an interference between these different possible future histories of the object.

However, this interference can exist only until the system is observed or disturbed. At that point, the interference between the waves vanishes, and the superposition is lost. The object has apparently experienced only one of the possible histories.

What does it mean for possible future histories to interfere? And for the wavefunction to collapse into just one of those histories? Those are tough questions. Currently, we know more about how to use this feature of quantum mechanics than what it means for the nature of our reality.

Sensing at the quantum level

Coherence is fragile and hard to protect. Perfectly isolated quantum objects and systems can maintain coherence indefinitely, but it would be impossible to manipulate or investigate them.

As a quantum object encounters other objects or fields, it picks up random influences from each. Even the act of measuring the object necessarily introduces noise, rendering its original wavefunction difficult—if not impossible—to decipher. As a result, the information that was stored in the coherent system is lost in a process called decoherence.

But for some applications, decoherence can be an advantage.

"If you prepare an object in a certain superposition of states with a certain coherence, and you send it into an environment with unknown influences, then a change in the object's phase relationship can provide meaningful information about the environment," said Jennifer Dionne, a professor of materials science and radiology at Stanford University and deputy director of Q-NEXT.

Here, the quantum object itself is the sensor. Because its phase relationship is so sensitive, it responds to subtle influences from the environment in a big way. This sensitivity could enable extremely high-resolution detection and imaging. Quantum coherence allows scientists to start off the sensor in a well-understood state that will persist over time. This makes it easier to retroactively determine how that state changed and what those changes mean about the environment.

For example, Dionne's lab is developing quantum sensors to detect force.

"We are studying how the colors of nanoparticles change when they encounter mechanical force within an organism," Dionne said. "We've started to deploy these sensors in living organisms using worms as test subjects. As the worms'

digestive tracts apply force, quantum transitions within the nanoparticle cause it to change color, which we can read out during digestion."

Atomic clocks and gravitational wave sensors also rely on quantum coherence for ultraprecision. Other examples of future sensing applications using quantum coherence include miniaturized magnetic resonance imaging (MRI) technologies, which could be used to scan single cells or molecules or significantly improve the resolution of whole-organism MRI scans.

Quantum coherence plays a role in biological systems, too. Scientists believe that birds use quantum coherence of proteins in their eyes to sense Earth's magnetic field for navigation, like an internal GPS. Researchers are developing magnetic field sensors using the same principles to help humans navigate in situations where satellite-based GPS is impossible.

Wave hello to quantum computing

One coherent object can serve as a great sensor. Two or more quantum objects that are coherent with each other enable quantum computation.

The traditional, or classical, bit in a computer can exist in one of two states, 0 or 1. Thanks to quantum superposition, a quantum bit—a qubit—can exist in a combination of the two states simultaneously. Coherence is responsible for maintaining the phase relationships, and therefore the superposition, between these states over time and space.

"In quantum computing, instead of doing operations such as addition or multiplication on classical bits, you're performing operations on different components of the waves that make up the wavefunction," Dionne said. "It's important to maintain coherence long enough so that as the computer performs operations, it isn't accumulating errors as the different parts of the wavefunction decohere."

Coherence is also responsible for maintaining entanglement, a special case of superposition that is crucial for quantum computing. When quantum objects are entangled, they maintain a particular correlation with each other even if they are physically separated by large distances.

"As long as two entangled objects remain coherent with each other, you can perform an operation on one of them, and that will give you information about the other," Dionne said.

Say you want to use a quantum computer to predict the success of a pizza party you plan to throw. First, you need to decide what factors would contribute to a successful party, such as the taste of the pizza and the number of guests. You might assign one qubit to represent the ratio of water to flour in your pizza dough, with 0 representing no water, 1 representing only water and the superposition between them representing all possible ratios. Another qubit could represent the number of people that show up, ranging from no one to everyone you invited. Perhaps a third qubit represents how likely you are to burn your food, and so on.

"You have all of these probabilities captured in clean, coherent states, and you let the system evolve over time," Holt said. "If you repeat the simulation enough, you get the probability of how successful the party will be based on the factors you encoded in the wavefunctions of the entangled qubits. But the simulation keeps going only if the states are coherent."

Because of the way information is embedded in the wavefunction, just a small number of qubits can represent very complicated, real-world problems with lots of dependencies, such as power grid optimization or finding the most energy-efficient way to distribute goods across the globe. The longer the system is coherent, the more complex the calculations can be.

Preserving quantum coherence

Holt's work at Argonne focuses on the development of matter-based qubits, where a defect—a replaced atom or an atomic vacancy, for instance—is embedded in a material's otherwise normal structure. Although scientists try to protect the defects from decoherence, small changes in temperature, pressure or magnetic fields can introduce noise.

Imagine you're running at the gym, and music is playing over the speakers. You notice it's difficult to run at your own pace rather than running to the beat of the music, and it's ruining your flow.

"There are a couple of ways to prevent this," Holt said. "You could wear earplugs so that you're isolated from the external influence, or you could start running significantly faster or slower so that it's easier to decouple your body's rhythm from that of the music. Then, even if the music changes, you don't care because you're just that far off from it."

To isolate qubits from noise, scientists keep quantum computers very cold—near absolute zero. They further decouple the qubits from their surroundings by designing and manipulating the states of the qubits to respond to frequencies of light or sound that their surroundings aren't affected by.

This is difficult to achieve, and different types of qubits are easier to protect than others. So far, the longest-lived qubits are called trapped atoms, which have been shown to remain coherent for several minutes or more. However, these qubits are difficult to use for computing applications. A recent demonstration of long-lived coherence was made by Q-NEXT scientists at Argonne and the University of Chicago. The team showed that a certain semiconductor qubit—a type of qubit that is more promising for quantum computing—stayed coherent for over five seconds.

"Preventing the loss of information through decoherence is the hard part of quantum information science, and that's why the field is called that," Holt said. "It's not just quantum science, it's information processing using quantum coherence."

Provided by Argonne National Laboratory

Newly discovered quantum state revolutionizes material science



A Princeton team has found a hidden chiral quantum state in a Kagome lattice material, breaking key symmetries and opening new paths in physics. (CREDIT: CC BY-SA 4.0)© The Brighter Side of News

In the natural world, many things come in mirror-image pairs. Your left and right hands are a perfect example—they look alike but can't be perfectly superimposed. This idea, called chirality or "handedness," is found everywhere in science, from the spiral of DNA to the twist of snail shells. For a long time, scientists believed certain materials didn't have this handedness. But a groundbreaking discovery has changed that thinking.

A team of researchers at [Princeton University](#), led by physics professor M. Zahid Hasan, has found a hidden chiral quantum state in a material long considered non-chiral. Their research, published in [Nature Communications](#), uncovered new behavior in a special type of material called a Kagome lattice. This result changes

what scientists thought they knew about how certain materials behave on a quantum level.

"This is somewhat like pointing the James Webb telescope at the [quantum world](#) and discovering something new," said Hasan. "We're finally able to resolve subtle quantum effects that had remained hidden in a topological quantum material."

Observation of the longitudinal circular photogalvanic effect in KV₃Sb₅. (CREDIT: Nature Communications)© The Brighter Side of News

How the Discovery Was Made

The Kagome lattice is a pattern of triangles named after a traditional Japanese basket design. It has become a go-to structure for studying strange [quantum effects](#) because of its geometry. Though it was assumed to be non-chiral, researchers noticed something odd a few years ago.

Back in 2021, Hasan's team found that under special conditions, a material made of potassium, vanadium, and antimony—KV₃Sb₅—formed a repeating pattern in its electron cloud called a charge density wave. This hinted at deeper, hidden behaviors. But while this clue was important, it didn't fully prove that the material had become chiral.

To find out for sure, graduate student Zi-Jia Cheng and postdoctoral researcher Shafayat Hossain built a special tool: a scanning photocurrent microscope, or SPCM. Unlike previous tools, this device shines circularly polarized light—light that spins either right or left—on the material. Then it measures the [electric current](#) produced in response.

At room temperature, the material showed no preference for the direction of light. But when cooled to just 4 degrees Kelvin (about -452°F), something fascinating happened. The material began to react differently to right- and left-handed light. This told the team they were seeing a new chiral state.

"Our measurements directly pinpoint broken inversion and mirror symmetries," Cheng explained. "This conclusively establishes the intrinsic chiral nature of the charge-ordered state in a [topological material](#) for the first time."

Why Chirality and Symmetry Matter

This discovery matters because symmetry is a basic idea in science. Many of the laws that govern the [universe](#) rely on the assumption that things are the same when flipped, rotated, or moved. When those symmetries break, new and surprising behavior can happen.

The change in KV_3Sb_5 is an example of a phase transition—a shift in state like water freezing into ice. But here, instead of water molecules lining up, electrons rearrange themselves into a chiral pattern. This process is called spontaneous symmetry breaking. It's been studied before in other systems, but never quite like this and never in this kind of topological material.

Temperature dependence of the longitudinal photocurrents highlighting a correlation with the CDW transition. (CREDIT: Nature Communications)© The Brighter Side of News

Topological materials are a special class of solids where the arrangement of electrons follows complex mathematical rules. These materials can host rare properties like [conducting electricity](#) only on their surface, or resisting heat and defects. The Kagome lattice in this study is particularly useful because it allows scientists to explore behaviors tied to both symmetry and topology.

The Princeton researchers built their devices with great care. Along with former postdoctoral fellow Qi Zhang, they created ultra-clean samples and chilled them using liquid helium. They measured how the material reacted when exposed to circularly polarized mid-infrared light, at wavelengths around 10.6 microns. They observed a strong response when the light's spin matched the material's internal chiral state—a sign of a phenomenon called the circular photogalvanic effect (CPGE).

The CPGE has become a powerful tool in recent years. It works by measuring how [electric currents](#) change depending on the direction of light spin. In this case, the presence of a CPGE signal directly proved that the material's internal structure was chiral. Even more, the direction and pattern of the signal revealed which symmetries had been broken.

Investigation on the origin of the circular photogalvanic effect. (CREDIT: Nature Communications)© The Brighter Side of News

A Long Debate Finally Settled

The discovery puts to rest years of debate among physicists. Since 2021, there's been disagreement over whether the charge-ordered state in KV_3Sb_5 actually breaks key symmetries or if those effects were caused by noise or imperfections. Earlier tools like scanning tunneling [microscopes](#) and electrical measurements had shown hints of chirality, but results were unclear and often contradicted each other.

By using both scanning photocurrent microscopy and theoretical modeling, this new study gave the strongest proof yet. The CPGE only appeared when the material entered its charge-ordered phase, and only along certain directions. This told the team that the material had broken both inversion and mirror symmetries but still kept some rotational features.

"Our study not only visualizes the [chiral nature](#) of the Kagome charge order, but also highlights the nonlinear photogalvanic effect as a sensitive probe for detecting subtle symmetry breakings," the authors wrote.

Even so, the science isn't completely settled. Hasan admitted, "We confirmed the phenomenon, but we don't yet have a rigorous theory as to why it occurs. We still don't fully understand it."

Symmetry breaking induced Chirality in KV_3Sb_5 . (CREDIT: Nature Communications)© The Brighter Side of News

That said, the path forward is bright. Understanding how and why symmetries break in these materials could one day lead to better ways of designing optoelectronic and [photovoltaic devices](#)—tools that convert light into electricity with high precision.

Standing on the Shoulders of Giants

This research is part of a long tradition at Princeton. The university has been home to many breakthroughs in quantum and topological physics. In 1985, the quantum Hall effect earned a Nobel Prize. Later, Princeton's Daniel Tsui won the 1998 Nobel Prize for the fractional quantum Hall effect. In 2016, F. Duncan

Haldane, another Princeton physicist, was honored for showing how topological states can arise in two-dimensional systems.

Hasan's own team made headlines in 2007 for discovering three-dimensional topological insulators. Since then, they've spent over a decade exploring how symmetry and topology interact. This latest discovery adds a new layer: a material that's both topological and chiral, with a charge-ordered quantum state that breaks multiple symmetries.

The team believes the same methods they used can help uncover similar hidden properties in other materials. As materials become more complex, especially with multiple layers of order like [magnetism](#) and superconductivity, tools like CPGE and scanning photocurrent microscopy may become essential.

Hasan sees no limits: "This is just the beginning. With these sensitive tools, who knows what hidden worlds of topological quantum matter we'll uncover next."