

Timeline of Quantum Evolution Over the Century

Sujal Sinha¹

¹School of Physical Sciences
National Institute of Science Education and Research

Publication Date: 2025/10/24

Abstract: In 1900, Max Planck introduced the quantum hypothesis, sparking a scientific revolution that would redefine physics and technology. Over the past century, Quantum mechanics has evolved from a spooky curiosity to a physical theory. In 1925, Heisenberg and Dirac introduced the concept of quantum mechanics, establishing the foundations of quantum theory. Since then, quantum entanglement has become a resource, enabling tasks such as teleportation, quantum key distribution (QKD), and even the foundational protocols of quantum cryptography. India's National Quantum Mission (2023-2031) likewise supports such achievements, with funding, thematic hubs, and strategic coordination to foster innovation in quantum communication, sensing, computation, and materials science. This essay explores the pivotal moments, scientists, and innovations that mark this extraordinary journey, highlighting the impact of World War II, first and second quantum revolutions and forecasting a future governed by quantum technologies.

Keywords: Quantum Mechanics, Superposition, Entanglement, Uncertainty, World War II.

How to Cite: Sujal Sinha (2025) Timeline of Quantum Evolution Over the Century. *International Journal of Innovative Science and Research Technology*, 10(10), 1060-1065. <https://doi.org/10.38124/ijisrt/25oct849>

I. INTRODUCTION

In the final days of the 19th century, a quiet but profound transformation began in physics. In 1900, German physicist Max Planck introduced the concept of quantized energy to resolve the blackbody radiation problem. He proposed that electromagnetic energy could be emitted or absorbed only in discrete packets—*quanta*—rather than in a continuous wave, leading to the formula $E = h\nu$, where h became known as Planck's constant [Planck, 1901]. Although intended as a mathematical fix, Planck's idea marked the earliest rupture in classical physics and laid the groundwork for a conceptual revolution.

Despite Planck's breakthrough, classical models continued to dominate physics through the early 20th century. That began to change slowly through contributions from Einstein's explanation of the photoelectric effect, Bohr's atomic model, and de Broglie's hypothesis of matter waves. But the true paradigm shift erupted in September 1925, when Werner Heisenberg's landmark paper was published in *Zeitschrift für Physik* [Heisenberg, 1925]. In this revolutionary work, Heisenberg discarded classical concepts, such as trajectories, and proposed a new formalism based on matrix algebra. His framework described atomic behavior through non-commuting operators, introducing uncertainty and non-determinism at the core of physical theory.

This marked the beginning of a radically new scientific paradigm. The foundational structure of quantum mechanics was built through the contributions of Max Born, Paul Dirac, and Erwin Schrödinger, whose wave mechanics provided an alternative—but ultimately equivalent—formalism to Heisenberg's matrix mechanics [Born, 1926, Dirac, 1930, Schrödinger, 1935]. Together, these developments formed a coherent, predictive, and experimentally verified system that redefined the very nature of matter and reality.

At its core, quantum mechanics introduced concepts such as superposition, entanglement, and uncertainty—ideas that defied everyday logic and challenged the philosophical foundations of science. In 1935, Einstein, Podolsky, and Rosen famously questioned whether quantum mechanics could be considered a complete theory, exposing its paradoxes in what became known as the EPR paper [Einstein et al., 1935]. Yet these conceptual tensions did not halt its scientific momentum. Rather, they fueled deeper inquiry, eventually proving foundational in fields like quantum information and cryptography.

The outbreak of World War II served as an unexpected and dramatic accelerant to the development of quantum physics. Driven by geopolitical urgency, massive resources and intellectual talent were directed toward understanding and controlling atomic phenomena. The result was the Manhattan Project, where quantum theory principles played a crucial role in the development of nuclear weapons [Rhodes, 1986]. Although the ethical implications of this application remain

deeply complex, it is also true that wartime investment accelerated quantum research in ways that peacetime science could not. It laid the ground- work for post-war advancements such as nuclear energy, quantum electronics, and eventually, quantum computing. Thus, the history of quantum mechanics is not one-dimensional: it is both a story of un- precedented scientific insight and a mirror reflecting the ethical responsibilities of human ingenuity.

This essay traces the journey from Planck's early insights to the formalization of quantum mechanics in 1925 and beyond. It explores how this theory not only revolutionized science but also reshaped technology, ethics, and the human thought—forming process.

II. EARLY DEVELOPMENTS

The decade following Heisenberg's 1925 publication marked a period of extraordinary intellectual cre- ativity, transforming quantum theory from a speculative framework into a full-fledged scientific revolu- tion. These early years—spanning 1925 to 1935—laid the theoretical bedrock for modern physics and showcased how deeply quantum mechanics diverged from classical intuitions.

Heisenberg's 1925 matrix mechanics, though revolutionary, was abstract and unfamiliar to many physi- cists [Heisenberg, 1925]. Recognizing this, Erwin Schrödinger introduced an alternative formulation in 1926, now known as *wave mechanics*. His model treated particles as wave-like entities described by the Schrödinger equation—a second-order differential equation governing the evolution of quantum sys- tems in space and time [Schrödinger, 1935]. While matrix and wave mechanics appeared different, they were soon shown to be mathematically equivalent, a realization that unified the quantum community.

Meanwhile, Max Born made a groundbreaking

conceptual leap by interpreting the square of the wave-function, $|\psi|^2$, as a probability density, thereby introducing a fundamental statistical nature to quantum mechanics [Born, 1926]. This probabilistic interpretation shifted physics away from deterministic tra- jectories and emphasized that only the likelihood of outcomes could be predicted—one of the most philosophically unsettling aspects of the theory.

Adding to the richness of the framework, Paul Dirac developed a relativistic version of quantum me- chanics in 1928, which predicted the existence of antimatter before it was discovered experimentally [Dirac, 1930]. Dirac's equation elegantly merged quantum mechanics with special relativity, marking one of the first successful steps toward a unified theory of physics.

During the same period, Wolfgang Pauli introduced the exclusion principle, explaining the structure of the periodic table, while Werner Heisenberg formalized the uncertainty principle in 1927, demonstrat- ing that certain pairs of physical properties—such as position and momentum—cannot both be known with arbitrary precision.

These milestones were not isolated. Instead, they formed a deeply interwoven fabric of theoretical insights. Each contribution—whether mathematical, philosophical, or experimental—reinforced and extended the others. By 1935, quantum mechanics was no longer a theoretical novelty but a predictive, experimentally validated framework reshaping physics at its foundations.

This period of early development, situated between Planck's foundational insight and the later tech- nological revolutions, marks the true consolidation of quantum mechanics as a scientific paradigm. It was not merely a transition in equations or experimental techniques—it was a transformation in how humanity understands the nature of reality itself.

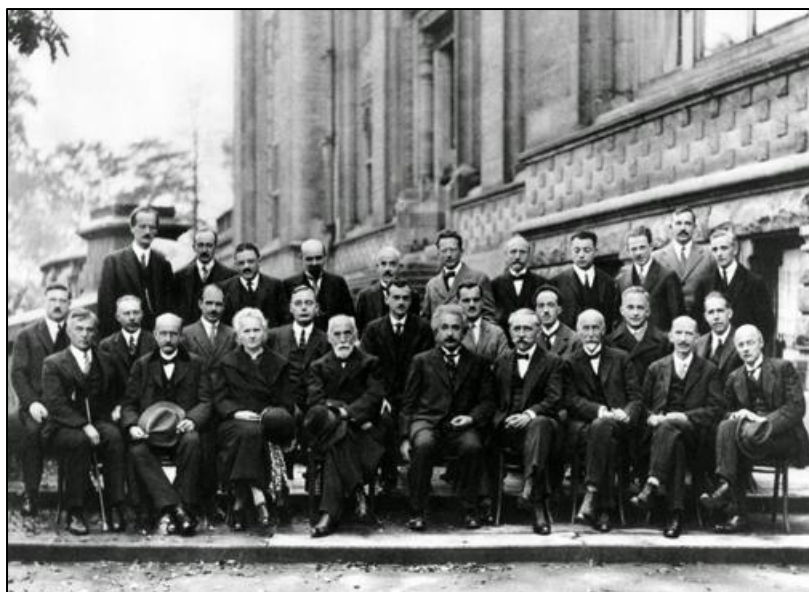


Fig 1: The 1927 Solvay Conference

➤ *Back Row*

Auguste Piccard, Émile Henriot, Paul Ehrenfest, Édouard Herzen, Théophile de Donder, Erwin Schrödinger, J.E. Verschaffelt, Wolfgang Pauli, Werner Heisenberg, Ralph Fowler, Léon Brillouin. Middle row: Peter Debye, Martin Knudsen, William Lawrence Bragg, Hendrik Kramers, Paul Dirac, Arthur Compton, Louis de Broglie, Max Born, Niels Bohr.

➤ *Front Row*

Irving Langmuir, Max Planck, Marie Curie, Hendrik Lorentz, Albert Einstein, Paul Langevin, Charles-Eugène Guye, C.T.R. Wilson, Owen Richardson.

Image Credit to "rarehistoricalphotos.com"

III. EXPERIMENTAL EVIDENCE

While quantum mechanics emerged as a theoretical framework in the 1920s, its acceptance and credibility were firmly anchored in a series of decisive experiments that defied classical expectations. These experimental validations not only confirmed quantum predictions but also exposed the limitations of classical physics, driving the scientific community toward this radical new paradigm.

One of the first and most influential confirmations came from the photoelectric effect, explained by Albert Einstein in 1905. In classical electrodynamics, light is treated as a continuous electromagnetic wave. The oscillating electric field of the wave interacts with the charged particles (electrons) in the metal. The electrons absorb energy from this field and, if they gain enough energy to overcome the binding forces (characterized by the work function of the metal Φ), they are emitted from the surface, thus producing a photocurrent. This research got Einstein his noble prize in the year 1921.

The Compton effect, discovered by Arthur H. Compton in 1923, provided further validation. Compton observed that X-rays scattered off electrons exhibited changes in wavelength, dependent on the scattering angle—evidence of particle-like momentum transfer between photons and electrons [Hamouda, 2020]. This experiment offered irrefutable proof of light's dual wave-particle nature and was among the strongest early endorsements of quantum theory.

In 1922, the Stern–Gerlach experiment offered direct insight into the quantization of angular momentum. When a beam of silver atoms passed through a non-uniform magnetic field, the atoms split into discrete beams rather than forming a continuous distribution as classical physics would predict. This provided concrete evidence for the quantization of spin and helped establish the foundation for quantum measurement theory.

Perhaps the most philosophically striking demonstration came from variations of the double-slit experiment. Initially used to demonstrate the wave nature of light, modern quantum versions—particularly those involving electrons—showed that individual particles exhibit interference patterns,

a signature of wave-like behavior. Even when particles are sent one at a time, an interference pattern still emerges over time, implying that each particle interferes with itself unless measured [Feynman, 1982]. These results support the idea of wavefunction superposition and challenge the classical notion of well-defined trajectories.

Together, these experiments reinforced the central predictions of quantum mechanics and established its legitimacy as a physical theory. They demonstrated not only that the quantum world behaves fundamentally differently from the classical, but also that this behavior is observable, repeatable, and quantifiable. Experimental evidence thus transformed quantum mechanics from a theoretical curiosity into one of the most robust and empirically grounded frameworks in the history of science.

IV. IMPACT OF WORLD WAR II ON THE GROWTH OF QUANTUM MECHANICS

The progression of quantum mechanics during the early 20th century was largely theoretical, with physicists exploring counterintuitive concepts like superposition, wave-particle duality, and quantization. However, the onset of World War II catalyzed a dramatic transformation: from an abstract theoretical field to one with tangible, world-altering consequences.

As nations grappled for technological supremacy, governments turned to physicists for solutions with strategic and military significance. This alignment of science and state gave rise to one of the most consequential scientific enterprises in history—the Manhattan Project. Initiated in 1942, it brought together many of the greatest minds in quantum theory and nuclear physics, including Niels Bohr, Enrico Fermi, and J. Robert Oppenheimer, under the goal of constructing an atomic bomb. Quantum mechanics provided the theoretical framework for understanding nuclear fission and chain reactions, essential for the design and function of atomic weapons [Rhodes, 1986].

The resulting devastation of Hiroshima and Nagasaki in 1945 remains a deeply complex legacy. It demonstrated the immense power of quantum-informed science, but also raised profound ethical questions about its application. While the bombings ended the war, they also introduced humanity to the era of existential risk. As Oppenheimer famously recalled from the Bhagavad Gita: "Now I am become Death, the destroyer of worlds."

However, the impact of World War II on quantum science was not solely destructive. The unprecedented scale of wartime investment led to vast improvements in research infrastructure, laboratory organization, and funding models. Many technologies developed during the war—such as nuclear reactors, radar, and early computing—laid the foundation for post-war scientific innovation. After 1945, these developments transitioned from military to civilian domains, giving rise to advancements like nuclear energy, quantum electronics, and the beginnings of quantum information theory.

In this light, World War II can be seen as both a crucible and a catalyst. It revealed the double-edged nature of quantum science—its capacity for both profound destruction and profound progress. The war pushed quantum mechanics from blackboard theory to engineering reality, shaping not only the outcome of a global conflict but the trajectory of science for decades to come.

V. FROM THEORY TO TECHNOLOGY: THE FIRST QUANTUM REVOLUTION

The end of World War II marked more than just the cessation of global conflict—it signaled the dawn of a new era in physics. The war had thrust quantum theory from the realm of thought experiments and laboratory puzzles into the geopolitical spotlight. Once viewed as abstract mathematics, quantum mechanics now had consequences measured in megatons and geopolitics [Rhodes, 1986].

Yet, out of this crucible emerged not only weapons, but also unprecedented opportunities. The scientific infrastructure built during the war—accelerators, detectors, and computational techniques—was repurposed for peaceful research. In the decades that followed, quantum mechanics migrated from blackboards to blueprints, launching what is now known as the First Quantum Revolution.

Unlike the theoretical revolution of the 1920s and 1930s, this was a revolution of engineering and application. A defining moment came in 1947 with the invention of the transistor at Bell Labs, a device whose operation fundamentally depends on quantum tunneling and semiconductor physics [Riordan and Hoddeson, 1997]. Transistors formed the backbone of the digital age and made possible the exponential rise of computation and communication technologies.

Soon after, quantum theory found another tangible manifestation in the development of the maser and later the laser, based on the principle of stimulated emission—a concept directly rooted in quantum electrodynamics [Townes, 1955]. Lasers have since become ubiquitous, finding applications in everything from medical surgery to fiber-optic communications.

Another striking example was the rise of magnetic resonance imaging (MRI) in medicine, grounded in principles of nuclear spin and quantum transitions in magnetic fields. The theoretical foundation for MRI was laid by physicist Felix Bloch in his 1946 paper on nuclear induction [Bloch, 1946].

Together, these developments demonstrated that quantum mechanics was not only accurate—it was *indispensable*. The First Quantum Revolution turned foundational physics into functional technology, embedding quantum theory into the infrastructure of modern civilization. From electronics and optics to diagnostics and data storage, quantum mechanics had moved out of the realm of intellectual curiosity and into the heart of human progress.

VI. THE SECOND QUANTUM REVOLUTION: HARNESSING QUANTUM SYSTEMS

While the First Quantum Revolution brought quantum principles into everyday devices, the Second Quantum Revolution—emerging prominently from the 1990s onward—focuses on directly manipulating and engineering individual quantum states. Unlike classical systems, quantum objects such as electrons, photons, and atoms exhibit properties like superposition, entanglement, and decoherence, which enable fundamentally new kinds of computation, communication, and sensing.

At the heart of this revolution is the concept of the qubit, or quantum bit, which can exist in a superposition of 0 and 1 simultaneously. This property allows quantum computers to explore vast computational spaces far more efficiently than classical computers for specific problems. Theoretical proposals by Richard Feynman and David Deutsch in the 1980s outlined the basic structure of quantum computing, but only in recent decades has the necessary quantum control become feasible [Feynman, 1982].

Quantum entanglement—once viewed as a “spooky” curiosity—has now become a resource. It enables tasks such as quantum teleportation, quantum key distribution (QKD), and even the foundational protocols of quantum cryptography, offering a level of security impossible with classical means [Gisin et al., 2002]. Real-world implementations of QKD have now been demonstrated over fiber networks and even in satellite communication systems.

Other advances include quantum sensing using nitrogen-vacancy centers in diamonds, enabling exquisitely sensitive magnetic and electric field measurements [Taylor et al., 2008]; quantum simulators for modeling complex molecules and condensed matter systems [Georgescu et al., 2014]; and superconducting circuits, which form the basis of many modern quantum processors including those developed by IBM and Google [Arute, 2019].

Governments and industries around the world have launched major initiatives to support this revolution. The European Union’s Quantum Flagship, the United States’ National Quantum Initiative Act (2018), and India’s National Mission on Quantum Technologies and Applications (2020) underscore the global importance of quantum research—not just in science, but also in economics, security, and international competition.

The Second Quantum Revolution represents more than technological progress; it is a shift in our relationship with nature. We are no longer passive observers of quantum systems—we are becoming active engineers of quantum reality. This revolution stands not only as a scientific milestone but as a gateway to a fundamentally new technological paradigm.

VII. QUANTUM TECHNOLOGIES FOR THE GOOD OF MANKIND

Modern quantum technology is proving its societal worth, moving beyond theoretical insight to practical, life-enhancing applications across healthcare, communication, and security.

In medicine, quantum principles such as nuclear spin underpin tools like MRI, and future quantum-enhanced sensors could revolutionize diagnostics. In communications, quantum key distribution (QKD) rooted in entanglement—offers encryption that is fundamentally tamper-evident and secure against adversarial attacks [Gisin et al., 2002].

A landmark demonstration occurred in June, 2025, where DRDO and IIT Delhi successfully validated free-space entanglement-based secure communication over a distance exceeding 1 km, achieving a secure key rate of 240 bps and quantum bit error rate below 7% under real-world conditions. This entanglement-assisted QKD eliminates the need for fibre-optic cabling, enabling deployment in dense urban or remote areas, and advancing India's strategic quantum communication capabilities.

Moreover, DRDO-led QKD trials have demonstrated fiber-based quantum key sharing over distances up to 100 km between cities, and 12 km between DRDO labs in Hyderabad, using time-bin protocols resistant to eavesdropping and supporting bit rates in the kilobit-per-second range. These experiments illustrate India's commitment to building quantum-secure infrastructure for defense, finance, and civilian applications.

India's National Quantum Mission (2023–2031) likewise supports such achievements, with funding, thematic hubs, and strategic coordination to foster innovation in quantum communication, sensing, computation, and materials science. Together, these initiatives point toward a future where quantum technologies are accessible, trusted, and ethical tools for national development and human welfare.

VIII. CONCLUSION

From Planck's 1900 quantization hypothesis to Heisenberg's 1925 formalism, through wartime urgency and technological innovation, quantum mechanics has continually reshaped our understanding of nature—and our capacity to shape the world. The First Quantum Revolution turned mathematical insight into everyday technology: transistors, lasers, MRI scanners—tools that power modern civilization. With World War II as both catalyst and crucible, quantum theory transitioned from academic abstraction to tangible force.

Today, the Second Quantum Revolution has entrusted us with unprecedented capabilities: entangled photons securing communication, qubits powering computation, sensors redefining precision. India's strides—such as DRDO's free-space quantum communication breakthrough and expansive National Quantum Mission—reflect this bold

new phase where quantum knowledge is engineered for good.

Quantum mechanics is no longer just a theory of atoms; it is a technology of nations. How we develop and apply these tools will determine whether quantum science becomes a blessing or a burden. The responsibility rests not only with scientists, but with society—ethical stewardship and inclusive deployment are as crucial as technical breakthroughs. In this light, Einstein's skepticism may serve as heed: we must not simply ask what quantum mechanics allows us to do, but what we ought to do with it.

REFERENCES

- [1]. [Arute, 2019] Arute, F. e. a. (2019). Quantum supremacy using a programmable superconducting processor. *Nature*, 574:505–510.
- [2]. [Bloch, 1946] Bloch, F. (1946). Nuclear induction. *Physical Review*, 70:460–474.
- [3]. [Born, 1926] Born, M. (1926). Zur quantenmechanik der stoßvorgänge. *Zeitschrift für Physik*, 37(12):863–867.
- [4]. [Dirac, 1930] Dirac, P. A. M. (1930). *The Principles of Quantum Mechanics*. Oxford University Press.
- [5]. [Einstein et al., 1935] Einstein, A., Podolsky, B., and Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47(10):777–780.
- [6]. [Feynman, 1982] Feynman, R. P. (1982). Simulating physics with computers. *International Journal of Theoretical Physics*, 21(6–7):467–488.
- [7]. [Georgescu et al., 2014] Georgescu, I. M., Ashhab, S., and Nori, F. (2014). Quantum simulation. *Reviews of Modern Physics*, 86:153–185.
- [8]. [Gisin et al., 2002] Gisin, N., Ribordy, G., Tittel, W., and Zbinden, H. (2002). Quantum cryptography.
- [9]. *Reviews of Modern Physics*, 74(1):145–195.
- [10]. [Hamouda, 2020] Hamouda, S. (2020). Compton scattering: A theory and experiments.
- [11]. [Heisenberg, 1925] Heisenberg, W. (1925).
- [12]. Über quantentheoretische umdeutung kinematischer und mechanischer beziehungen. *Zeitschrift für Physik*, 33:879–893.
- [13]. [Planck, 1901] Planck, M. (1901). On the law of distribution of energy in the normal spectrum. *Annalen der Physik*, 4:553–563.
- [14]. [Rhodes, 1986] Rhodes, R. (1986). *The Making of the Atomic Bomb*. Simon and Schuster.
- [15]. [Riordan and Hoddeson, 1997] Riordan, M. and Hoddeson, L. (1997). *Crystal Fire: The Birth of the Information Age*. W. W. Norton Company.
- [16]. [Schrödinger, 1935] Schrödinger, E. (1935). Die gegenwärtige situation in der quantenmechanik.
- [17]. *Naturwissenschaften*, 23(49):823–828.
- [18]. [Taylor et al., 2008] Taylor, J. M., Cappellaro, P., and Childress, L. e. a. (2008). High-sensitivity diamond magnetometer with nanoscale resolution. *Nature Physics*, 4:810–816.

- [19]. [Townes, 1955] Townes, C. H. (1955). The maser—new type of microwave amplifier, frequency standard, and spectrometer. *Bell System Technical Journal*, 34(4):587–593.