A History of Quantum Mechanics

Quantum Mechanics Day, April 14, 2024.
Presented to the Science Circle of the Second Life virtual world.

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Known as Scire Gaea in Second Life

For this presentation, I will cover highlights of the history of quantum mechanics. The agenda is for me to talk for about 30 minutes and then open for discussion, especially as several scientists in the audience are directly involved in this field or are closely associated with it. They may wish to relate exciting points. I also know that 30 minutes is usually when my voice begins to die.

World Quantum Day

https://worldquantumday.org/

The World Quantum Day is celebrated on April 14, a reference to 4.14, the rounded first digits of Planck's constant: $4.1356677 \times 10^{-15}$ eV·s = 0.000 000 000 000 004 1356677 electron volt second, a product of energy and time that is the fundamental constant governing quantum physics.

The World Quantum Day aims at engaging the general public in the understanding and discussion of Quantum Science and Technology.

It is a decentralized and bottom-up initiative, inviting all scientists, engineers, educators, communicators, entrepreneurs, technologists, historians, philosophers, artists, museologists, producers, etc., and their organisations, to develop their own activities, such as outreach talks, exhibitions, lab tours, panel discussions, interviews, artistic creations, etc., to celebrate the World Quantum Day around the World.

The occasion of this presentation is World Quantum Day, celebrated annually on April 14th.

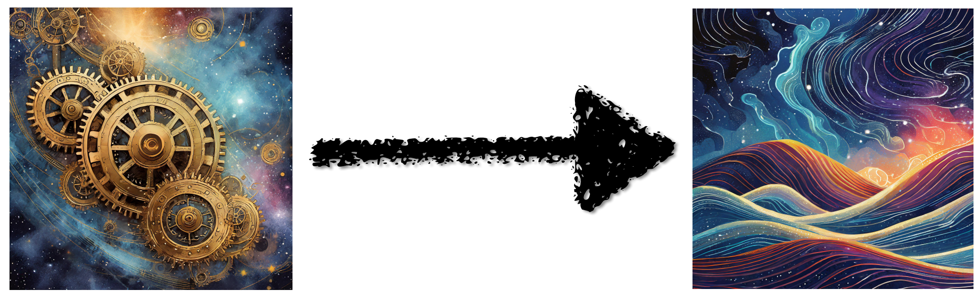
Agenda

- Max Planck and the Birth of Quantum Theory (1900)
- Albert Einstein and the Quantum Theory of Light (1905)
- Niels Bohr's Model of the Atom (1913)
- De Broglie's Hypothesis (1924)
- Heisenberg's Matrix Mechanics (1925)
- Schrödinger's Wave Mechanics (1926)
- The Copenhagen Interpretation
- Paul Dirac and Quantum Electrodynamics (1928)
- Quantum Entanglement and EPR Paradox (1935)
- Feynman and Quantum Electrodynamics (1940s-1950s)
- Many-Worlds Interpretation (1957)
- Modern Experiments in Quantum Mechanics

Historically, quantum mechanics originated with a recognition of the inadequacy of the classical view in the years leading up to 1900. Over the next third of a century, hampered by World War One, the controversial ideas of quantum mechanics were debated and, with limitations, accepted. Ramifications are still hotly debated today. We will look at the failures of the classic view and the insightfulness of the principal scientists of this early period. The agenda listed here shows the significant milestones in the development of the theory.

Introduction to Quantum Mechanics

- Definition and significance of quantum mechanics.
- The Clockwork Universe becomes a Probabilistic Universe.



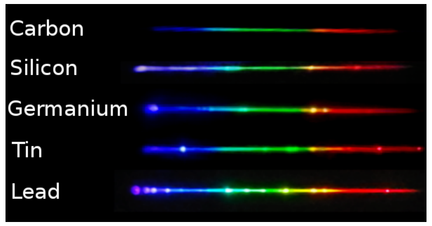
Before 1900 CE, the universe seemed to be clockwork. The governing laws had definitive, unique solutions. Knowledge of the present provided a complete prediction of the future and the past. This had disturbing consequences for questions of free will and the nature of life, but many in Western European science found this worldview logical and even comforting.

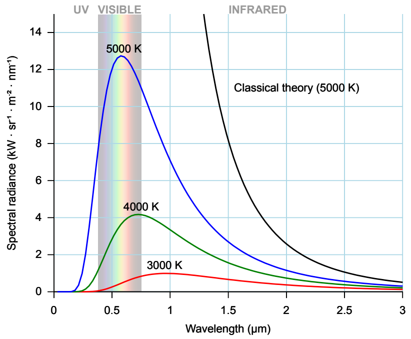
- Tik Tok -

The laws of thermodynamics and electrodynamics were triumphs of the 19th century.
However, the relation of these laws to underlying phenomena was not clear at the time.
The scientists of the late 1800s knew of the electron as a particle.
They understood electromagnetic radiation as waves.
The existence of atoms was widely accepted.
There were also observational flaws.
Materials heated to a given temperature glowed with specific colors.
Spectroscopy, available from the early 1800s, showed both a continuous emission spectrum and unexplained emission and absorption lines.
However, when thermodynamic calculations were applied, the calculated behavior
was observationally wrong because it showed that emission power increases without limits for shorter wavelengths. This was called the ultraviolet catastrophe.

Max Planck and the Birth of Quantum Theory (1900)

- Planck's solution to the black-body radiation problem.
- Introduction of the quantum of action (Planck's constant).
- The idea is that energy is quantized.





Max Planck had struggled with the problem since 1894. He the insight that birthed quantum theory. On October 19th, 1900, he introduced the idea that energy is quantized to solve the black-body radiation problem. Only certain energies could be allowed.

Planck suggested that energy could only be emitted or absorbed in discrete packets, which he called "quanta."

This was a significant departure from classical physics, which treated energy as continuous.

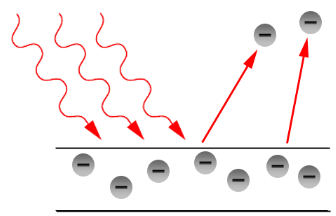
Planck's fundamental constant emerged from his work.

However, Planck stated that he had no explanation for the new formula for the black-body emission. It fitted the data that was all.

Classical mechanics was still correct, providing that only integer multiple values of physical quanta were allowed for any given physical property, e.g., energy, magnetism, etc. A physicist had to guess what the given quanta might be. Then, in 1905, Albert Einstein became 26 years old and changed everything.

Albert Einstein and the Quantum Theory of Light (1905)

- Photoelectric effect and the concept of light quanta (photons).
- Wave-particle duality of light.
- Einstein's contribution to quantum theory's foundation.



In 1905, Albert Einstein expanded on Planck's ideas by applying the concept of quantization to light. He proposed that light could be described as particles, later called photons, in addition to waves. This is different from just having energy levels described by quanta; now, Einstein holds that the carrier of light is itself in quanta. Isaac Newton suggested that light could be particles, but the wave phenomenon based on Christiaan Huygens' observations, the Young experiment, and Maxwell's equations became the dominant theory until Einstein. This explanation was crucial for understanding the photoelectric effect, where light on a metal surface ejects electrons. Einstein's work provided strong evidence for the duality of light as waves or particles, depending on the observational circumstances. Some years later, in 1921, the Nobel Prize was awarded to Einstein in recognition of this result.

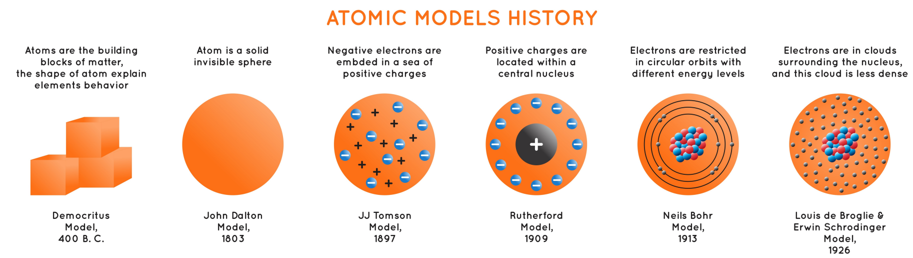
The Structure of Atoms
Rutherford

- Also, in 1905, Ernest Rutherford conducted experiments that revealed atoms' internal structure as having a heavy small nucleus.
- In 1913, Bohr worked out the emission of hydrogen atoms with a proposed structure of electrons around the atomic nucleus.
- In 1915, Wilson and Sommerfeld considered the effect on position and speed.

Also, in 1905, Ernest Rutherford, 16 years older than the young Einstein, conducted experiments that revealed atoms' internal structure. Neils Bohr, the youngster in Rutherford's laboratory, introduced quantization ideas for the hydrogen atom. This successfully explained the emission lines of hydrogen (but not of heavier atoms), considerably strengthening the old quantum theory. In 1915, William Wilson (age 40) considered the effect of energy quantization on position and speed. Sommerfeld extended that work.

Niels Bohr's Model of the Atom (1913)

- Postulates of the Bohr model.
- Explanation of atomic spectra.
- Limitations of the Bohr model.



Niels Bohr introduced his model of the atom in 1913, which incorporated quantum theory to explain the behavior of electrons in atoms. Bohr proposed that electrons orbit the nucleus in specific allowed paths or orbits and can only gain or lose energy by jumping from one orbit to another. This model helped explain atomic spectra, particularly the hydrogen spectrum, and was a crucial step in developing quantum mechanics. In the diagram, the evolution of conceptual models of atoms moves from indivisible units to puddings of positive and negative charges, orderly nuclei, Bohr's orbitals, and probabilistic clouds.

Electron Orbits - not feasible?

- The idea of sharp orbits for electrons around an atomic nucleus needed to be revised.
  - Shouldn’t the orbits decay as the orbiting electrons generate electromagnetic radiation?
  - While the model worked with hydrogen, larger atoms were not modeled correctly.
  - An angular momentum of zero was not possible in the model.
- Bohr recognized this.

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Other Problems with the Old Quantum Theory

The post WWI period, about 1922 - 1923

- helium problem - spectra still not calculable
- anomalous Zeeman effects - spectra lines split when the atoms are in a magnetic field.
- According to Max Born "At Göttingen we also took part in the attempts to distill the unknown mechanics of the atom out of the experimental results. . . . The art of guessing correct formulas . . . was brought to considerable perfection."
- Werner Heisenberg (age 23) was particularly good at producing systematic tables of allowed physical quantities.

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De Broglie's Hypothesis (1924)

- Wave-particle duality extended to matter (de Broglie wavelength).
- The conceptual foundation for wave mechanics.
- Impact on the understanding of electron behavior in atoms.

Louis de Broglie proposed a groundbreaking idea in 1924: particles like electrons could exhibit wave-like behavior. This extended duality to all of matter, like light with wave and particle characteristics. De Broglie's hypothesis is a central concept in quantum
mechanics. But if everything can be a wave and a particle, does everything have a wave equation?

The Effect of Allergy Attacks

1925

- Heisenberg suffered from allergies. Springtime in Göttingen is not a good place to be if you have allergies.
- Max Born allowed Heisenberg to rest from Göttingen by vacationing to the North Sea island of Helgoland.
- As his health improved, Heisenberg started reading Goethe and working on physics, as one would in those circumstances.
- He organized the physical properties in a matrix related to old QM rules.

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Heisenberg's Matrix Mechanics (1925)

- Werner Heisenberg, Max Born, and Pascual Jordan
- Introduction of matrix mechanics.
- The uncertainty principle.
- Transition from classical to quantum mechanics.

Bohr's followers did not consider physical models of electrons as waves or particles or dualities.
They preferred to focus on the quantities that were directly connected to experiments.
This became the “shut up and calculate” attitude toward understanding Quantum Mechanics.

Until now, quantum mechanics was a collection of ideas without a computation methodology. Werner Heisenberg’s matrix mechanics was the first formalism of quantum mechanics. He introduced the uncertainty principle, stating that it's impossible to simultaneously know a particle's position and momentum with absolute precision. This principle challenged the determinism of classical mechanics and introduced a probabilistic approach to understanding the physical world.

The tik-tok of the universe was now in peril.

Principles of QM Matrix Mechanics

- Observed properties are quantized.
- The state of a physical system does not assign definite values to properties.
- Measurement pulls out a definite value per the probabilities.
- Statements about a property value are meaningless until measured.
- The order of measurements for several properties will alter the outcomes.
- If the Planck constant is taken as zero, the equations become classical.

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Let's consider a simplified example where we measure the spin of an electron along the z-axis. The spin can be +ħ/2 (spin up) or -ħ/2 (spin down).

$$|\uparrow\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad |\downarrow\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

The spin operator for measuring the spin along the z-axis in units of ħ/2 can be represented by the matrix:

$$\hat{S}_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

To find the expected value of the spin for an electron in the spin-up state,
we calculate the matrix product of the transpose conjugate of the state vector, the operator, and the state vector itself:

$$\langle\uparrow|\hat{S}_z|\uparrow\rangle = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 1$$

$$|\Psi\rangle = c_1|\uparrow\rangle + c_2|\downarrow\rangle$$

Schrödinger's Wave Mechanics (1926)

- Meanwhile, in during Christmas of 1925, and independent of the Heisenberg work, Edwin Schrödinger had his own ideas.
- Wave functions and probability amplitudes.
- The concept of superposition.
- It was offered as an alternative to matrix mechanics.
- Later, matrix mechanics and the wave equation were shown to be equivalent and consistent methods.

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Schrödinger's equation, a fundamental equation in quantum mechanics, allows for the prediction of the probability distribution of a particle's position. His work provided a more intuitive understanding of quantum phenomena and has become a cornerstone of quantum mechanics. But Schrödinger was not happy with his equation. He did not like the probabilistic aspects of QM. In 1935, his thought experiment about the life and death of a cat was an attempt to show the absurdity of probabilistic interpretations. Everyone else said, “Hey, great, that is exactly what happens!” Schrödinger was bitter about it for the rest of his life.

Matrix Mechanics vs Wave Equation

- The Schrödinger equation was a familiar mathematical form.
- Matrix Mechanics introduced novel notation and methods.
- For these reasons, the Schrödinger equation introduced a few months after matrix mechanics, was initially favored.

Matrix Mechanics vs Wave Equation
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• For these reasons, the Schrödinger equation had more initial acceptance.

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They showed that the differences were superficial. The two forms were equivalent.

Solvey Conferences

- Instituted by Belgian industrialist Ernest Solvey and supported by the King of Belgium

- First conference in 1911, invitation only, included Albert Einstein, Marie Curie. Ernest Rutherford, Henri Poincaré, W. Nernst, M. Brillouin, E. Solvay, H. Lorentz, E. Warburg, J. Perrin, W. Wien, R. Goldschmidt, M. Planck, H. Rubens, A. Sommerfeld, F. Lindemann, M. de Broglie, M. Knudsen, F. Hasenöhrl, G. Hostelet, E. Herzen, J. H. Jeans, E. Rutherford, H. Kamerlingh Onnes, P. Langevin.

- Because of WWI tensions, the third and fourth conferences lacked essential contributors.

- The fifth conference in 1927 was the major one, including A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, and Th. De Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin. P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, **N. Bohr**, I. Langmuir, M. Planck, M. Skłodowska-Curie, H.A. Lorentz, **A. Einstein**, P. Langevin, Ch. E. Guye, C.T.R. Wilson, O.W. Richardson

Fifth Solvey Conference of 1927

held in Brussels

- Albert Einstein (paraphrasing): “God does not play dice.”
- Niels Bohr (exact quote): “Stop telling God how to behave!”
- Einstein wanted to show that QM uncertainty was not rational.
  - Each day of the conference, Einstein would propose a new thought experiment contradicting QM.
  - Bohr would ponder it overnight and have a rebuttal in the morning.
  - This debate dominated the conference and continued for the next several years.

The Fifth Solvey Conference of 1927, held in Brussels, was dominated by Einstein and Bohr.
Einstein: Quantum mechanics is very impressive. But an inner voice tells me it is not yet real. The theory produces a good deal but hardly brings us closer to the secret of the Old One. At all events, I am convinced that He does not play dice.
Bohr: Why not?

The Copenhagen Interpretation

- Bohr, Heisenberg, and the philosophical underpinnings.
- Observer effect and wave function collapse.
- Implications for the reality of quantum states.

The Copenhagen interpretation, primarily developed by Bohr and Heisenberg in the late 1920s, posits that quantum particles don't have definite properties until observed and that quantum mechanics can only predict probabilities. This interpretation has been influential but controversial, leading to various alternative interpretations.

The Copenhagen Interpretation

There is no single definitive statement of the Copenhagen Interpretation

- Quantum Mechanics is indeterministic.
- The results provided by measuring devices are classical.
- The Born rule: the wave function of a system yields probabilities for the outcomes of measurements upon that system.
- Certain properties cannot be jointly defined for the same system simultaneously.
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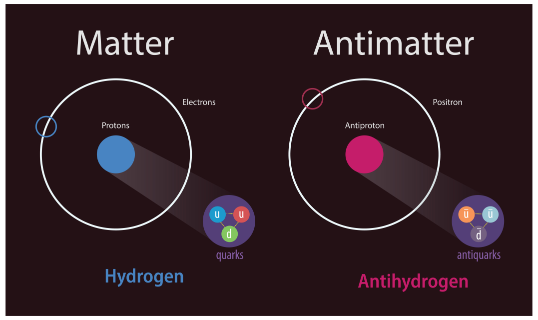
Paul Dirac and Quantum Electrodynamics (1928)

- Dirac equation for relativistic quantum mechanics.
- Prediction of antimatter.
- Foundation of quantum field theory.



Paul Dirac formulated a version of quantum mechanics that incorporated special relativity, leading to the prediction of antimatter. In 1928, he developed the Dirac equation, which described the behavior of electrons at relativistic speeds. His work was fundamental to developing quantum electrodynamics (QED), a theory that explains how light and matter interact.

Linus Pauling and Chemical Bonds (1931)

- The electron-pair bond was formed through the interaction of an unpaired electron on each of two atoms
- The spins of the electrons had to be opposed.
- Each electron can participate in only one pair at a time.
- The strongest bonds are made using electrons of the lowest possible energy level.
- The strongest bonds are formed where the electron probabilistic distributions of each atom overlap, as shown by the wave equation.

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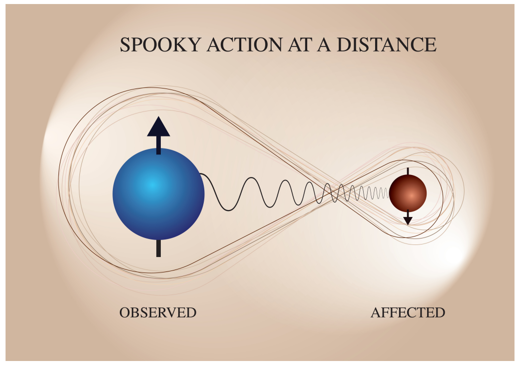
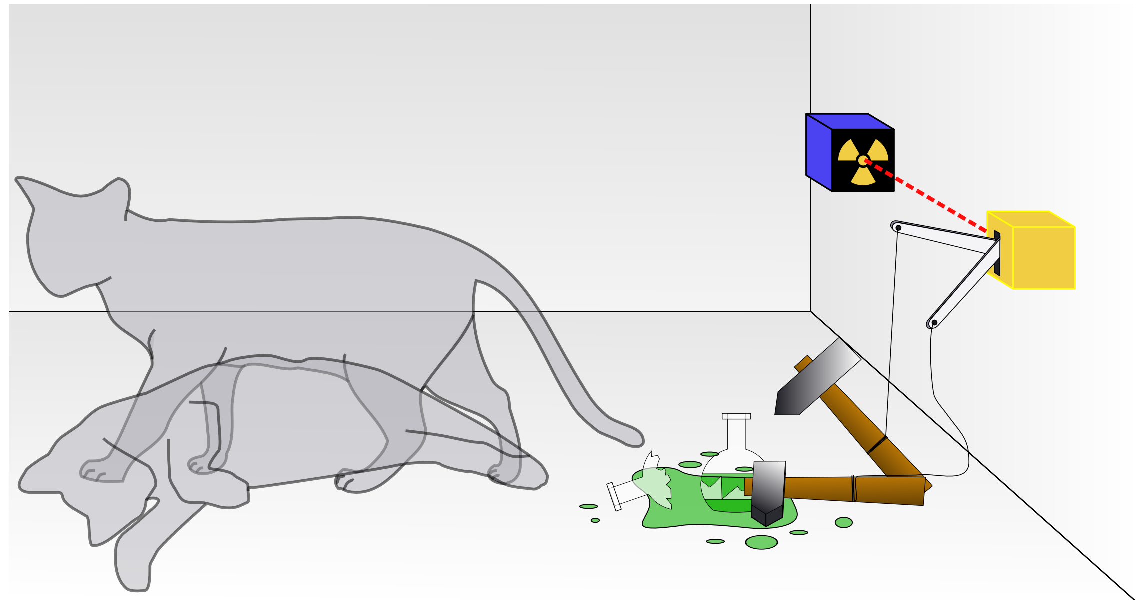
Quantum Entanglement and EPR Paradox (1935)

- Explanation of quantum entanglement.
- Einstein-Podolsky-Rosen paradox challenging action at a distance.
- Bell's theorem and experimental tests.
- Schroedinger's Cat in a Box challenging probabilistic interpretations.



Quantum entanglement, a phenomenon where particles become interconnected such that the state of one instantly influences the state of the other, was at odds with theory of special relativity. To get around this, Einstein, Podolsky, and Rosen in 1935, suggested that QM might be a statistical theory of an underlying deterministic reality. This sparked debates about the nature of reality in quantum mechanics. The problem is known as the EPR paradox.



The with the cat in the box is that you can not separate the quantum evolution of the observer from that of the cat. Each belongs to the same quantum system.

Cat in a box…

- When they opened the box, there was a whole different possibility they hadn't even considered.

Besides, there are other ways the system could evolve.

Anyone who has a cat knows that cats can break quantum rules.

Other Interpretations

- Von Neumann: a conscious observer is needed.
  - Wigner: such observers become part of the probabilistic system.
- Bohr: The occurrence of irreversible processes causes the collapse of wave functions.
  - Per the cat in a box, the Geiger counter triggers the collapse.
- Einstein-Podolsky-Rosen: hidden variables (1935)
  - Bell: we can test that. (1964)

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No Hidden Variables

Realism, Determinism, locality

- Realism: observers are not needed for the universe to exist.
- Determinism: knowledge of the present determines the future, and the past.
- Locality: no action at a distance
- QM Completeness: QM is a true picture of the universe.

The Bell Test shows that you can not have

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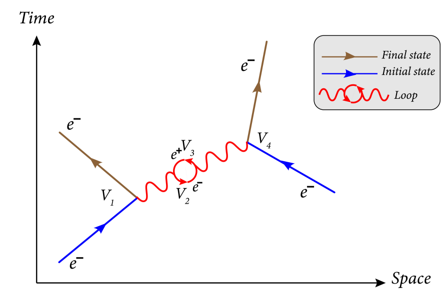
Feynman and Quantum Electrodynamics (1940s-1950s)

- Feynman diagrams and the simplification of quantum field theory calculations.
- Renormalization in QED.
- Feynman's contributions to the interpretation of quantum mechanics.



Richard Feynman, Julian Schwinger, and Sin-Itiro Tomonaga developed a reformulated QED in the 1940s and 1950s. Feynman's introduction of Feynman diagrams provided a powerful visual tool for understanding and calculating interactions between particles in QED. His work significantly advanced the knowledge of electromagnetic interactions at a quantum level.

Many-Worlds Interpretation (1957)

- Hugh Everett's proposal of the many-worlds interpretation.
- The idea of parallel universes in quantum mechanics.
- Debates and philosophical implications.

The Many-Worlds Interpretation, proposed by Hugh Everett in 1957, offers a radical perspective on quantum mechanics. It suggests that all possible outcomes of quantum measurements are physically realized in some "world" or universe. This interpretation removes the need for wave function collapse by positing that all possible outcomes of quantum events occur in separate, non-interacting branches of the universe.

Modern Experiments in Quantum Mechanics

- Quantum mechanics at large scales (macroscopic quantum phenomena).
- Quantum coherence and decoherence.
- Recent groundbreaking experiments.

Recent experiments in quantum mechanics have continued to challenge and expand our understanding of the quantum world.
These include tests of quantum
entanglement, quantum computing, and quantum teleportation, demonstrating the strange, non-local properties of quantum particles.
Advances in quantum computing have shown potential for solving problems far beyond the reach of classical computers, using principles like superposition and entanglement. Moreover, experiments in quantum cryptography have opened new frontiers in secure communication. These modern experiments test the fundamentals of quantum mechanics and pave the way for practical applications that could revolutionize technology, security, and information processing.

Conclusion: The Ongoing Journey of Quantum Mechanics

- Summary of quantum mechanics' impact on various fields.
- Open questions and the frontiers of quantum physics.
- The interdisciplinary nature of quantum research and its future prospects.