

UNIT-I: Introduction to Quantum Theory and Technologies

The transition from classical to quantum physics, Fundamental principles explained conceptually: Superposition, Entanglement, Uncertainty Principle, Wave-particle duality, Classical vs Quantum mechanics – theoretical comparison, Quantum states and measurement: nature of observation, Overview of quantum systems: electrons, photons, atoms, The concept of quantization: discrete energy levels, Why quantum? Strategic, scientific, and technological significance, A snapshot of quantum technologies: Computing, Communication, and Sensing, national and global quantum missions: India's Quantum Mission, EU, USA, China.

Introduction

Quantum computing is a revolutionary field at the intersection of computer science, physics, and mathematics. It leverages the principles of quantum mechanics to process information in fundamentally different ways from classical computers.

In classical computing, information is stored in bits that can be either 0 or 1. In quantum computing, information is stored in quantum bits, or qubits, which can exist in a superposition of 0 and 1 at the same time. This allows quantum computers to perform certain types of calculations much faster than classical computers. In 2019, Google's quantum computer did a calculation in less than four minutes that would take the world's most powerful supercomputer 10,000 years to do.

Quantum computers use the entanglement of qubits and superposition probabilities to perform operations. These operations can be manipulated so that certain probabilities are increased or decreased, which leads us to the correct and incorrect answers we're looking for.

The transition from classical to quantum physics








The transition from classical to quantum physics represents a fundamental shift in our understanding of the universe, particularly at the atomic and subatomic levels. Classical physics, which describes the motion of macroscopic objects, fails to accurately predict the behavior of very small particles. Quantum mechanics or physics, describes the motion of microscopic particles for understanding the probabilistic nature of these particles and their interactions. This introducing the concepts like quantization, wave-particle duality and superposition.

In the second half of the 19th century it seemed that the laws of classical mechanics, developed by Newton, Lagrange, Hamilton, Jacobi and Poincare's, the Maxwell theory of electromagnetic phenomena and the laws of classical statistical mechanics could account for all

known physical phenomena. After several decades of experimental and theoretical work, that one has to formulate a new kind of mechanics, which reduces to classical mechanics in a suitable limit.

At the end of the 19th century, classical physics had progressed to such a level that many scientists thought all problems in physical science had been solved or were about to be solved. After all, classical Newtonian mechanics was able to predict the motions of celestial bodies, electromagnetism, thermodynamics laws and classical optics allowed the design and construction of scientific instruments such as the telescope and the microscope, both of which had advanced the understanding of the physical world around us.

A planetary-like situation where the electrons are held in orbits by centrifugal forces was not plausible because of the radiative energy loss an orbiting electron would experience. This dilemma was one of the causes for the development of quantum mechanics. In addition, there were other experimental results such as black body radiation, photoelectric effect Compton effect and spectral line emission or absorption. These could not be explained by classical physics and needed the development of new theoretical concepts as mechanics, in the 1920s that led to the formulation of quantum mechanics.

Phenomenon	Can be explained in terms of waves.	Can be explained in terms of particles.
Reflection	 ✓	•→ ✓
Refraction	 ✓	•→ ✓
Interference	 ✓	•→ ⊗
Diffraction	 ✓	•→ ⊗
Polarization	 ✓	•→ ⊗
Photoelectric effect	 ⊗	•→ ✓
Compton scattering	 ⊗	•→ ✓

Four key principles of quantum mechanics

1. **Superposition:** Superposition is the state in which a quantum particle or system can represent not just one possibility, but a combination of multiple possibilities.
2. **Entanglement:** Entanglement is the process in which multiple quantum particles become correlated more strongly than regular probability allows.
3. **Decoherence:** Decoherence is the process in which quantum particles and systems can decay, collapse or change, converting into single states measurable by classical physics.

4. **Interference:** Interference is the phenomenon in which entangled quantum states can interact and produce more and less likely probabilities.

Classical vs Quantum Mechanics - theoretical comparison

Feature	Classical Mechanics	Quantum Mechanics
Origin	Developed by Newton, Lagrange, and Hamilton (17th–19th century).	Emerged in the early 20th century (Planck, Schrödinger, Heisenberg, etc.).
Scale	Macroscopic (large-scale objects like planets and cars)	Microscopic (atoms, electrons, photons)
Nature	Deterministic (precise predictions)	Probabilistic (only probabilities of outcomes)
Key Theories	Newton's Laws, Electromagnetism, Thermodynamics	Schrödinger's Equation, Heisenberg's Uncertainty Principle, Quantum Field Theory
Mathematical Framework	Uses differential equations: Newton's laws, Lagrangian, Hamiltonian.	Uses linear algebra: wavefunctions, operators, Hilbert space.
Wave-Particle nature	Objects are either particles or waves.	Quantum mechanics shows wave particle duality.
Uncertainty	No fundamental uncertainty. Only certainty as particle	Heisenberg Uncertainty Principle: $\Delta x \cdot \Delta p \geq \hbar/2$
Superposition	Objects exist in a single definite state	Particles can exist in multiple states simultaneously
Entanglement	No concept of entanglement	Particles can be instantaneously correlated regardless of distance
Technology	Engines, satellites, bridges, classical optics.	Lasers, transistors, quantum computers, MRI, semiconductors.

Origin of Quantum mechanics

Origin of Quantum mechanics had its roots at the failure of Newton's laws of motion to explain the behavior of microscopic world of atom.

- In 1900 Max Planck proposed a new theory called quantum theory which successfully explained the energy distribution among different wavelengths in the blackbody radiation (Energy is quantized), Specific heat of solids, Photoelectric effect, Compton effect, Hydrogen atom spectra etc.
- Electromagnetic waves carry discrete energy packets and more intense light corresponds to more photons, not higher energy photons.
- Wave-particle duality: This concept was first proposed by Louis de Broglie in 1924 and was later confirmed by experiments.
- Black body radiation,

Basic postulates of Quantum Mechanics

The basic postulates of quantum mechanics are:

- The state of a quantum system is described by a wavefunction Ψ , which is governed by Schrodinger wave equation.
- Observable quantities are represented by Hermitian operators.

Important examples of Hermitian operators includes the Hamiltonian energy operator, momentum operator, and position operator.

Let A be a linear operator. Its Hermitian adjoint, denoted A^\dagger , then

$$\langle \Psi | A | \Psi \rangle = \langle \Psi | A^\dagger | \Psi \rangle^*$$

Where: $\langle \Psi |$ and $| \Psi \rangle$ are Bra-ket notation representing vectors in a Hilbert space.

* denotes the complex conjugate.

A and A^\dagger are the operator and adjoint, respectively.

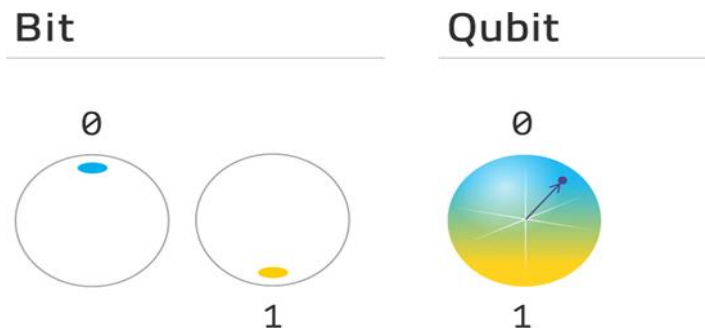
If $A = A^\dagger$, then the operator A is Hermitian.

- The only possible result of a measurement of an observable is one of the eigenvalues of the corresponding operator.
- The probability of obtaining an eigenvalue is given by the square of the absolute value of the eigenstate. i.e., $P = | \langle a_n | \Psi \rangle |^2$

Qubits

While classical computers rely on binary bits (zeros and ones) to store and process data, quantum computers can encode even more data at once using quantum bits, or qubits.

A qubit can behave like a bit and store either a zero or a one, but it can also be a weighted combination of zero and one at the same time. When combined, qubits in superposition can scale exponentially. Two qubits can compute with four pieces of information, three can compute with eight, and four can compute with sixteen like 2^n .



Q- bit representation

Basis states of Qubit: Each qubit can be in one of the two basis states $|0\rangle$ or $|1\rangle$.

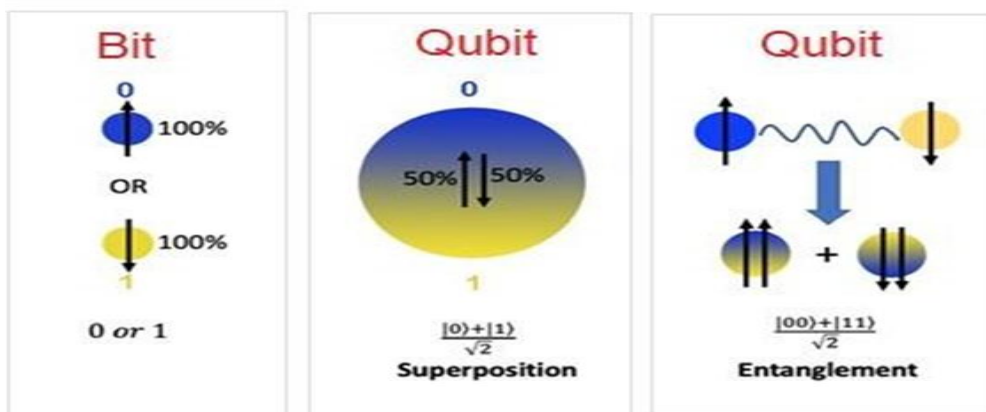
Combined basis system: A two-qubit system combines the quantum states of two qubits into a single quantum state, representing all possible combinations of the individual qubit states. This system lives in a 4-dimensional Hilbert space.

$|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$ These are the computational basis states, formed by the tensor product of the individual qubits

Mathematical Representation

For two qubits $|q_1\rangle$ and $|q_2\rangle$, the combined state is given by the tensor product:
 $|\psi\rangle = |q_1\rangle \otimes |q_2\rangle$.

For example: If $|q_1\rangle = |0\rangle$ and $|q_2\rangle = |1\rangle$, $|\psi\rangle = |0\rangle \otimes |1\rangle$



Fundamental principles explained conceptually

The fundamental principles of quantum physics conceptual explanation were done by the following four: Superposition, Entanglement, Uncertainty Principle, and Wave-Particle Duality each explained in intuitive, non-mathematical terms.

Superposition:

One of the most fundamental idea of quantum mechanics is that its equations are linear with respect to the wave function Ψ . Thus, sum of two solutions of a linear equation again satisfies the same equation. This statement concerning “the possibility of representing a single wave function in terms of the sum of other wave functions is called the superposition principle”. The principle of superposition of states is one of the important principles of quantum mechanics.

According to this principle, if a certain quantum-mechanical system has an allowed state Ψ' and also state Ψ'' , then the possibility of single wave system Ψ can also exist in a state described by the function

$$\Psi = c' \Psi' + c'' \Psi'' = \alpha |0\rangle + \beta |1\rangle$$

where c' and c'' are arbitrary complex numbers.

Given several solutions of the time-independent Schrodinger equation with different values E_n of the energy, any linear superposition of the form

$$\Psi = \sum_n c_n \Psi_n$$

will also be a solution of the Schrodinger wave equation.

Let Ψ_1 and Ψ_2 be two wave functions representing two physically allowed states of a given object. Then any linear superposition of the form

$$\Psi = a_1 \Psi_1 + a_2 \Psi_2$$



also describes the states of the object. a_1 and a_2 are arbitrary complex coefficients. Repeated applications of the superposition principle shows that if the principle holds for the superposition of two wave functions, it also holds for the superposition of an arbitrary number of wave functions.

Entanglement:

Entanglement is a fundamental concept in quantum mechanics that describes a quantum correlation between quantum systems. When two or more qubits are entangled, the state of one qubit is dependent on the state of the other qubit, even if they're far apart. This quantum correlation is a unique feature of quantum systems that doesn't have a classical counterpart.

Entanglement is the process in which multiple quantum particles become correlated more strongly than regular probability allows.

If $|\Psi_A\rangle$ and $|\Psi_B\rangle$ are the states of subsystems A and B respectively then $|\Psi_{AB}\rangle$ is the joint state of the composite system, entanglement statement written mathematically, as

$$|\Psi_{AB}\rangle = |\Psi_A\rangle \times |\Psi_B\rangle = \alpha_1 |00\rangle + \alpha_2 |01\rangle + \alpha_3 |10\rangle + \alpha_4 |11\rangle$$

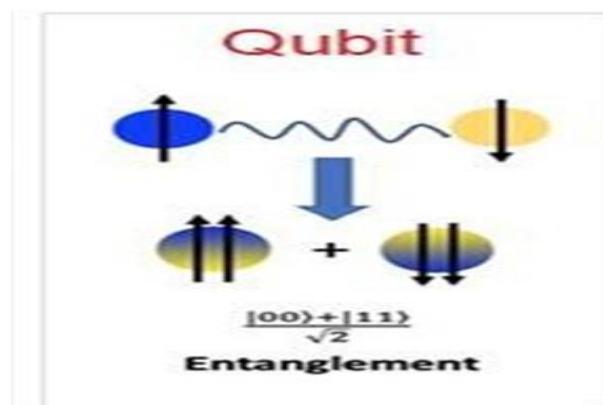
Entangled states exhibit several remarkable properties, including non-separability, non-local correlations, and superposition of states. These features distinguish entangled states from classical systems and lie at the heart of many quantum phenomena.

Entangled States Representation

Entangled states are those that cannot be expressed as a product of states belonging to the individual subsystems. Mathematically, an entangled state $|\Psi\rangle$ of a composite system cannot be written as:

$$|\Psi\rangle = |\psi\rangle_1 \otimes |\phi\rangle_2$$

for any $|\psi\rangle_1$ in H_1 and $|\phi\rangle_2$ in H_2 . Instead, entangled states exhibit correlations between the subsystems that are not present in separable states.



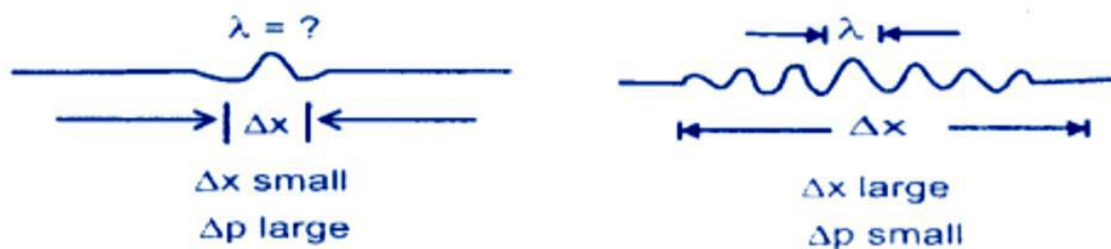
Uncertainty Principle:

According to classical mechanics, it is to find the position and momentum of a moving particle. In quantum mechanics, there is a great uncertainty about finding the exact location of the particle.

In 1927, Heisenberg proposed the uncertainty principle.

“It is impossible to determine both exact position and momentum of a moving particle at the same time.”

- ❖ In a narrow wave packet, the position of the particle can be accurately determined, but not the wavelength. As a result, the particle's momentum cannot be measured accurately as there are not enough waves to exactly measure the wavelength ($\lambda = \frac{h}{mv}$).
- ❖ On the other hand, in a wider wave packet, the wavelength can be determined exactly but the position of the particle will be uncertain due to the large width of the wave packet. Hence, it can be concluded that it is impossible to simultaneously determine the exact position and the exact momentum of particle.



If Δx and Δp are the uncertainties of the position and momentum respectively then

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$
$$\Delta x \Delta p \geq \frac{\hbar}{2} \quad \left[\text{where } \hbar = \frac{h}{2\pi} \right]$$

Another form of uncertainty concerns energy and time is

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

Applications:

1. Using uncertainty principle, non-existence of electrons in the nucleus can be proved.
2. Existence of protons, neutrons and α particles in the nucleus is confirmed by the uncertainty principle.
3. Binding energy of an electron in an atom can be calculated from this uncertainty principle.

4. Emission of radiation of light from an excited atom is also confirmed by this principle.

Wave particle duality:

Wave-particle duality refers to the fundamental property of matter where, at one moment it appears like a wave, and yet at another moment it acts like a particle. This dual naturality followed by new kind of wave called matter wave.

Light exhibits the phenomena of interference, diffraction, polarization, photoelectric effect and Compton Effect. Interference, diffraction and polarization can be explained by wave nature of light. The photoelectric effect and Compton Effect are explained by particle nature of light. So, light has dual nature that is wave nature and particle nature.

In 1924, Louis De-Broglie proposed that the material particles like electrons, protons, neutrons exhibit wave nature; these are called matter waves or De-Broglie's waves.

$$\text{De-Broglie's wavelength or matter wave wavelength } \lambda = \frac{h}{mv}$$

He proposed this without any strong experimental support and hence called hypothesis.

De-Broglie hypothesis:

The dual nature of light possessing both wave and particle properties was explained by combining Plank's expression for energy of a photon $E = h\nu$ with Einstein's mass energy relation $E = mc^2$.

$$\therefore h\nu = mc^2$$

But we know, $\nu = \frac{c}{\lambda}$, we get

$$\frac{hc}{\lambda} = mc^2 \text{ or } \lambda = \frac{h}{mc} = \frac{h}{p} \quad (\text{where } p \text{ is the momentum of the photon})$$

The wave length λ is called De-Broglie wavelength.

It is defined as the ratio of Plank's constant to the momentum of a particle.

$$\therefore \lambda = \frac{h}{mv} = \frac{h}{p}$$

The above equation is known as the De-Broglie wave equation for wavelength of matter waves

Quantum states and measurement

In quantum mechanics, a quantum state represents the condition of a physical system, and measurement is the process of extracting information about that system. Measurements in

quantum mechanics differ fundamentally from classical measurements because they are inherently probabilistic and can alter the quantum state being measured.

Quantum States:

- A quantum state is a mathematical description of a quantum system, often represented by a wave function or a density matrix.
- It encapsulates all that can be known about a system at a given time.
- Unlike classical systems where properties have definite values, quantum systems can exist in superpositions of multiple states simultaneously.
- For example, a qubit (quantum bit) can be in a superposition of 0 and 1 until measured.

Quantum Measurement:

- A quantum measurement is a process that extracts information about a quantum system.
- It's not just revealing a pre-existing property, but rather actively influencing the system.
- **Probabilistic Outcomes:** Quantum measurements have probabilistic outcomes. The Born rule dictates how to calculate the probabilities of different measurement outcomes.
- **Wavefunction Collapse:** When a measurement is made, the quantum state “collapses” into a definite eigenstate corresponding to the measured value. This means the superposition is lost, and the system settles into a single, specific state.
- **Example:** If you measure the position of an electron, the wavefunction collapses to a specific location, and you only get one measurement result (the position of the electron at that moment).

Distinguishing quantum states and measurement

Measurement plays a central role in quantum mechanics. An act of measurement disturbs a quantum system in a fundamental way. Consider once again a general qubit

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$$

When a measurement is made, the qubit will be forced into the state $|\psi\rangle \rightarrow |0\rangle$ or $|\psi\rangle \rightarrow |1\rangle$. After measurement the original state is lost. It isn't possible to make a measurement and determine what α and β are.

The measurement of a quantum system involves some type of interaction or coupling of that system with a measuring device. That device can be thought of as part of the larger environment

which the quantum system is a part of larger environment is known as the ancilla. A system coupled to an environment is known as an open system. The systems considered in that case were closed quantum systems that is, systems that were isolated from the larger environment. The time evolution of a closed quantum system can be is governed by the Schrodinger equation, and we say that closed quantum systems evolve over time via unitary evolution.

Let's summarize the axioms of quantum mechanics briefly here, focusing on what we need to begin a discussion of measurement. First, we know that a quantum system is described by a vector (the "state vector") in a Hilbert space. The state of the system at time t is denoted by $|\psi(t)\rangle$. The dynamical behavior of a quantum system is determined by the Hamiltonian operator H , which describes the total energy of the system. The time evolution of an isolated or closed system is described by the Schrodinger equation

$$i\hbar \frac{\partial \Psi}{\partial t} |\psi\rangle = H\Psi \quad \text{----- 1}$$

The actual form of the Hamiltonian operator depends on the specific nature of the system being studied. However, the general solution equation 1 is gives us the state of the system at time t . If we let the state of the system at the initial time $t=0$ be $|\psi(0)\rangle$, then the solution of equation 1 tells us how quantum states evolve with time:

$$|\psi(t)\rangle = e^{\frac{-iHt}{\hbar}} |\psi(0)\rangle \quad \text{----- 2}$$

Looking at Eqn. 2 and recalling that the Hamiltonian is Hermitian, we see that $e^{\frac{-iHt}{\hbar}}$ is a unitary operator. This operator is called unitary evolution operator:

$$U = e^{\frac{-iHt}{\hbar}} \quad \text{----- 3}$$

Finally, we described the evolution of a quantum system in terms of density operators.

Nature of observation

In quantum mechanics, observation is not a passive act of simply noticing something. Instead, it's an interaction that fundamentally alters the quantum system being observed. This interaction forces the system to "choose" a specific state, causing a phenomenon known as wave function collapse. Essentially, before observation, a quantum system can exist in a superposition of multiple states, but the act of observation collapses this superposition into a single, definite state.

Superposition:

Quantum systems, like electrons, can exist in a superposition of states. For example, an electron can be in multiple locations or have multiple spin orientations simultaneously until measured.

The Observer Effect:

The act of observing or measuring a quantum system inevitably disturbs it. This disturbance forces the system to "choose" one specific state from the superposition, causing the wave function to collapse.

Not Just Visual Observation:

Observation in quantum mechanics doesn't require a conscious observer or even a human. Any interaction between a quantum system and another system (like a measuring apparatus) can be considered an observation and can lead to wave function collapse.

Examples:

The double-slit experiment demonstrates this effect. When electrons are fired through two slits, they create an interference pattern (like waves) if not observed. However, when we try to determine which slit the electron passes through (by placing a detector), the interference pattern disappears, and the electrons behave like particles.

Implications:

The nature of observation in quantum mechanics is a profound concept, highlighting the interconnectedness of quantum systems and the role of interaction in determining their behavior. Some interpretations even suggest that the universe "observes" itself through these interactions.

[Overview of quantum systems: electrons, photons, atoms:](#)

The **overview of quantum systems**—focusing on **electrons**, **photons**, and **atoms**—which are foundational components in quantum physics and quantum technologies:

1. Electrons:

Electrons are **elementary particles** with **negative charge** and **intrinsic spin- $\frac{1}{2}$** , making them **fermions**.

Key Quantum Properties:

- **Wave-Particle Duality:** Electrons exhibit both wave-like and particle-like behavior (e.g., in double-slit experiments).
- **Spin:** Intrinsic angular momentum, leading to quantum magnetic behavior.

- **Quantized Energy Levels:** In atoms, electrons occupy discrete energy levels (orbitals).
- **Pauli Exclusion Principle:** No two electrons can occupy the same quantum state in a system.

Applications:

- **Quantum dots:** Artificial atoms where single electrons can be trapped and manipulated.
- **Spintronics:** Devices leveraging electron spin rather than charge.
- **Quantum computing:** Electron spin used as a qubit (e.g., in silicon or quantum dots).

2. Photons:

Photons are **massless bosons** that mediate the **electromagnetic force**. They always move at the speed of light in vacuum.

Key Quantum Properties:

- **No rest mass:** Always travel at C , the speed of light.
- **Quantization of Energy:** Energy $E=h\nu$, where h is Planck's constant and ν is frequency.
- **Polarization:** A quantum degree of freedom analogous to spin.
- **Entanglement:** Easily entangled in polarization or time-bin degrees of freedom.

Applications:

- **Quantum optics:** Study and manipulation of light at the quantum level.
- **Quantum communication:** Secure transmission using quantum key distribution (QKD).
- **Photonic quantum computing:** Using photons as qubits in linear optical systems.

3. Atoms:

Atoms consist of a **nucleus (protons and neutrons)** surrounded by **electrons** in quantized orbitals.

Key Quantum Properties:

- **Discrete Energy Levels:** Electrons can transition between levels by absorbing/emitting photons.
- **Superposition & Coherence:** Atomic states can exist in coherent superpositions.
- **Hyperfine States:** Atomic energy levels split due to nuclear spin—used in atomic clocks and qubits.

- **Interaction with Light:** Atoms absorb, emit, and scatter photons in quantized ways.

Applications:

- **Atomic clocks:** Use precise frequency of atomic transitions.
- **Bose-Einstein condensates:** Atoms cooled to near absolute zero behave collectively in a single quantum state.
- **Trapped-ion quantum computing:** Individual atoms used as qubits, manipulated via lasers.

The concept of quantization: discrete energy levels

In physics, **quantization** refers to the idea that certain physical quantities—like energy—can only take on **discrete (specific, fixed)** values, rather than a continuous range.

- **Classical Physics:** Energy is continuous. A particle can have *any* amount of energy.
- **Quantum Physics:** Energy is discontinuous and is **quantized**—it comes in "packets" or "quanta".

Key Concept: Discrete Energy Levels

In quantum systems (like electrons in an atom), particles can only occupy specific energy states. These are often visualized as "**energy levels**".

Example: The Hydrogen Atom

- An electron in a hydrogen atom can only exist in certain allowed energy levels.
- It **cannot** have energy values between these levels.
- When it moves from one level to another, it absorbs or emits a **photon** with energy equal to the difference between the levels.

Formula for hydrogen energy levels: $E_n = \frac{13.6 \text{ eV}}{n^2}$

Where:

E_n = energy of level n

n = principal quantum number (1, 2, 3, ...)

Furthermore, the quantization explains phenomena like:

- **Atomic spectra** (discrete lines of light emitted/absorbed)
- **Stability of atoms** (electrons don't spiral into the nucleus)
- **Semiconductor behavior**, lasers, and other quantum technologies

Another Example: Particle in a one-dimensional infinite well (Box)

Formula for energy particle in potential box:

$$E = \frac{n^2 h^2}{8 m a^2}$$

Why Quantum? Strategic, Scientific, and Technological Significance

The term "quantum" in quantum computing refers to the use of quantum mechanics – specifically principles like superposition, entanglement, and quantum interference – to process information in ways that classical computers can't.

1. Strategic significance

1). National Security & Defense

- Quantum radar, navigation, and secure communications can outmatch current military technologies.
- Quantum technologies are part of strategic competition among global powers (US, China, EU, India, etc.).

2). Cybersecurity

- Quantum computing threatens classical encryption (RSA, ECC).
- Quantum cryptography is a potential countermeasure, establishing **post-quantum security**.

3). Economic Competitiveness

- Nations leading in quantum tech will dominate future economic and technological infrastructures.
- Quantum industry is projected to be a **trillion-dollar economy** in the coming decades.

4). Global Scientific Leadership

- Investment in quantum research boosts a nation's prestige, talent retention, and innovation leadership.
- Quantum technologies are seen as a pathway to dominance in next-generation technological fields, such as AI, computing, and communications.

2. Scientific Significance

1). Fundamental Understanding of Nature

- Quantum theory is the most accurate and comprehensive framework for describing physical phenomena at atomic and subatomic scales.
- It underlies our understanding of matter, energy, and the universe itself (e.g., particle physics, cosmology, quantum field theory).

2). New Paradigms of Reality

- Concepts like **superposition**, **entanglement**, and **nonlocality** challenge classical notions of determinism, locality, and reality.

3). Quantum Simulation

- Quantum computers have the potential to simulate phenomena that are impossible to model with today's most powerful supercomputers, opening new frontiers in chemistry, material science, and even biology.

3. Technological Significance

1). Quantum Computing

- Solves classically intractable problems (e.g., factoring large numbers, simulating quantum systems, optimization).
- Potential to revolutionize AI, materials science, pharmaceuticals, and cryptography.

2). Quantum Communication

- Enables **ultra-secure** data transmission via **quantum key distribution (QKD)** and **quantum networks**.
- Offers defense against classical and quantum hacking.

3). Quantum Sensing & Metrology

- Ultra-sensitive measurement tools (e.g., atomic clocks, magnetometers, gravimeters).
- Applications in GPS, medical imaging, geology, defense, and navigation (especially in GPS-denied environments).

4). Quantum Materials

- Enables development of high-T_c superconductors, topological insulators, and spintronic devices.
- Foundation for new generations of energy-efficient electronics and memory.

Snapshot of Quantum Technologies

Quantum technologies are revolutionizing industries by harnessing the principles of quantum mechanics for practical applications. The three main areas of quantum technologies that are seeing significant growth are **Quantum Computing**, **Quantum Communication**, and **Quantum Sensing**. Each of these has its own set of challenges and promises, and countries around the world are heavily investing in their development.

Quantum Computing:

Quantum and classical computers both try to solve problems, but the way they manipulate data to get answers is fundamentally different. But quantum computers are unique by introducing two principles of quantum mechanics crucial for their operation, superposition and entanglement.

Quantum computing uses quantum physics to solve problems at speeds not possible with classical computers. The basis of quantum computing is the “qubit” (short for “quantum bit”). Conventional computers use “bits,” which can represent either “1” or “0.” In contrast, qubits can

simultaneously represent 1, 0, or any value in between. This property (called “superposition”) allows a quantum computer to perform many operations simultaneously and in parallel, allowing for computations millions of times faster than those of classical computers.

- **Applications:** Quantum computing holds the potential to revolutionize fields such as cryptography, material science, drug discovery, machine learning, and optimization problems. Tasks that would take classical computers millennia could be completed in minutes or hours.
- **Challenges:** One of the primary obstacles is maintaining **quantum coherence**. Quantum systems are very fragile, and even slight disturbances can disrupt computations. **Scalability** and **error correction** are major research areas.

Quantum Communication:

Quantum communication applies the properties of quantum physics to provide better security and improved long-distance communications. Quantum communication provides two advantages for security.

First, in conventional digital communication, messages are encrypted and decrypted using keys and transmitted as classical bits (zeros or ones). Quantum key distribution (QKD) allows the creation of encryption keys that are encoded and transmitted using qubits, making them more difficult to break.

Second, qubits are incredibly sensitive. Any attempt to disrupt or even just observe them will force qubits to collapse. This means that if an outside observer tries to intercept or monitor communications that use QKD, their activity will be immediately noticed by the message recipient. Quantum communications therefore hold the potential to protect transmitted data and make it very difficult for eavesdroppers to evade detection.

QKD has been demonstrated over fiber optic cables, radio, and satellite relays. However, fiber optics can transmit QKD over only short distances, and space-to-ground demonstrations have been inconclusive.

- **Applications:** Quantum encryption promises unbreakable security, and it can also enable **quantum networks**, which could eventually form the backbone of a **quantum internet**. This would vastly improve the security of financial transactions, personal communications, and government data exchanges.

- **Challenges:** Quantum communication networks are limited by the fact that quantum information can't travel long distances without being lost. Advances in **quantum repeaters** and **quantum satellites** are crucial to overcoming this barrier.

Quantum Sensing:

Quantum sensing allows for extremely precise measurements. The technology can capture high-resolution and highly sensitive measurements at the level of individual atoms, providing greatly improved accuracy. Quantum sensing technologies have a broad range of applications, including healthcare and medical research, environmental monitoring, construction, energy, navigation, and defense.

- **Applications:** Quantum sensors could improve GPS systems, enable precise timekeeping for financial systems, monitor environmental changes, and even assist in the detection of gravitational waves.
- **Challenges:** The biggest issue is cost and integration into existing infrastructure, although ongoing miniaturization of quantum devices is helping.

National and Global Quantum Missions

Countries around the world recognize the importance of quantum technologies for the future and are developing national quantum missions to lead the charge in this transformative field.

India's Quantum Mission:

India has made strides in quantum research and development, and the Indian government has launched the **National Mission on Quantum Technologies & Applications (NMQTA)**. Launched in 2020, this mission has a budget of **₹8,000 crores** (approx. \$1 billion) and aims to establish India as a global leader in quantum technologies.

- **Key Focus Areas:** The mission focuses on quantum communication, quantum computing, quantum cryptography, quantum sensors, and quantum materials.

- **Research Institutions:** India has strong institutions like the **Indian Institute of Science (IISc)**, **Tata Institute of Fundamental Research (TIFR)**, and **Indian Institute of Technology (IIT)** that are actively engaged in quantum research.
- **Quantum Workforce:** There's also an emphasis on creating a quantum workforce and promoting innovation through collaborations with industry players and startups.

European Union (EU):

The **EU Quantum Flagship** program is one of the most ambitious European-wide initiatives to drive quantum technology research. With a budget of **€1 billion** for the period of 2018-2028, the goal is to make Europe a leader in quantum technologies by creating **quantum communication infrastructure**, **quantum computing**, and **quantum simulation** capabilities.

- **Key Areas of Focus:** The EU is heavily invested in **quantum communication** (specifically quantum encryption), **quantum computers** that can solve practical problems, and **quantum sensors** for applications in healthcare and industry.
- **Collaboration:** The EU is promoting partnerships between universities, research centers, and private industries. Countries like **Germany**, **France**, and **the Netherlands** are already global leaders in quantum research.

USA:

The **United States** has been a leader in quantum research and continues to invest heavily in its development through federal agencies like the **National Quantum Initiative (NQI)**, established in 2018. The NQI is a coordinated effort among federal agencies like **DOE**, **NSF**, **DARPA**, and the **National Institute of Standards and Technology (NIST)**.

- **Key Focus Areas:** Quantum computing (particularly for national security and industrial applications), **quantum cryptography**, and **quantum networks**.
- **Private Sector:** Companies like **IBM**, **Google**, **Microsoft**, and **Intel** have made major breakthroughs in quantum computing, and the U.S. is home to leading quantum startups.
- **Investment:** The U.S. government has committed billions of dollars to quantum research, and President Biden's administration has shown an increased focus on ensuring the U.S. remains a leader in quantum technology.

China:

China has aggressively pursued leadership in quantum technologies, seeing them as a crucial aspect of national security and economic development. The Chinese government has poured substantial resources into quantum research and has some notable achievements.

- **Key Areas of Focus:** China has focused on **quantum communication**, having launched the **world's first quantum satellite, Micius**, which has demonstrated **quantum key distribution** over long distances. The country is also investing heavily in **quantum computing** and **quantum sensing**.
- **State-Driven Investments:** The Chinese government has established several national quantum research institutions and has provided large-scale funding through "**Made in China 2025**", a policy that focuses on advancing quantum technologies among other critical fields.
- **Global Ambition:** China's aggressive strategy includes international collaborations and securing leadership in quantum technologies.