

Quantum Technology:

Government of India approved **National Quantum Mission (NQM)**, a strategic initiative in **2023**, which aims to position India as a global leader in the emerging field of **quantum technologies**. Quantum technologies are based on postulates of quantum mechanics, the science of the very small and very cold, where laws of classical physics fail.

National Quantum mission to be implemented by Department of Science and technology over 8 years (2023–2031) has been allocated a budget of about ₹6,000 crore.

Targeted Research Areas: The mission will focus on four major domains:

1. **Quantum Computing:**
 - Develop **quantum computers** with varying qubit capacities:
 - 50-100 qubits in the near term.
 - 1,000 qubits and more in the long term.
2. **Quantum Communication:**
 - Deploy a **quantum key distribution (QKD)** network over distances of 2,000 km.
 - Build satellite-based quantum communication systems.
3. **Quantum Sensing and Metrology:**
 - Develop sensors for highly sensitive measurements in defense, healthcare, and energy sectors.
 - Enhance precision in atomic clocks and navigation systems.
4. **Quantum Materials and Devices:**
 - Research materials for **quantum dots, single-photon sources**, and other advanced quantum devices.

Quantum Computing:

Quantum computing is an advanced form of computing that harnesses the principles of quantum mechanics. It represents a paradigm shift in how we process information, making it a topic of great importance for science, technology, and policy discussions.

Working of Quantum Computing is based on Qubits, building blocks of quantum computing. In a classical computer data is stored and processed in bits (binary Units) i.e., 0 and 1.

Qubits leverage two key quantum properties:

1. **Superposition:** A qubit can be in multiple states (0 and 1) simultaneously.
2. **Entanglement:** Qubits can be interconnected such that the state of one directly affects the state of another, even over large distances.

As the number of qubits increase the computational capacity of quantum computer increases exponentially.

Applications of Quantum Computing



1. **Cryptography:**
 - Quantum computers can break many existing encryption methods, posing challenges for cybersecurity.
 - However, **quantum cryptography** (like quantum key distribution) can create unbreakable encryption.
2. **Drug Discovery and Healthcare:**
 - Quantum simulations can model molecular interactions with high accuracy, speeding up drug discovery and personalized medicine.
3. **Artificial Intelligence (AI) and Machine Learning:**
 - Quantum computing enhances data analysis, optimization, and machine learning algorithms, enabling faster AI development.
4. **Weather Forecasting and Climate Modeling:**
 - Quantum computers can process complex climate models more efficiently, improving predictions of extreme weather events.
5. **Optimization Problems:**
 - Useful in industries like logistics, finance, and energy for solving large-scale optimization problems.
6. **Material Science:**
 - Quantum simulations can help design new materials with desired properties, benefiting industries like energy, electronics, and construction.
7. **National Security:**
 - Quantum technology can bolster secure communications, advanced radar systems, and strategic planning.

Quantum supremacy is the ability of quantum computers to solve problems that classical computers cannot in a realistic amount of time. **Google's Sycamore**

Google's quantum computer, Sycamore, was able to solve a problem in 3 minutes and 20 seconds that Google estimated would take a classical supercomputer 10,000 years to solve.

Challenges of Quantum Computing

- **Quantum Decoherence:**
 - Quantum computers require extremely stable environments (near absolute zero temperatures) to operate without errors.
 - Qubits are highly fragile and prone to "decoherence," where their quantum state is lost.
- **Scalability:** Current quantum computers are limited in scale, with only a few hundreds of qubits. Building large-scale, fault-tolerant quantum computers remains a challenge.
- **Software and Algorithms:** Quantum programming involves concepts that are fundamentally different from classical programming, making it more challenging to develop software for quantum systems.
- **Cooling Requirements:** Superconducting qubits, one of the leading technologies for building quantum computers, require temperatures close to absolute zero to function.
- **Cybersecurity Risks:** Quantum computers could break current encryption systems, threatening global cybersecurity.
- **High Cost:** Building and maintaining quantum computers is expensive and resource-intensive.
- **Workforce Shortage:** There is a lack of skilled professionals in quantum computing.

More about Data Encryption and strength of Quantum Computer:

Encryption is the process of converting plaintext into ciphertext to protect data from unauthorized access. It ensures confidentiality, integrity, and authenticity of information during storage or transmission.

While Symmetric Encryption Uses a single key for both encryption and decryption, **Asymmetric Encryption uses two keys**, a public key for encryption and a private key for decryption. Public keys can be shared openly, while private keys are kept secret.

For example, in **Public key distribution**, a pair of keys (public and private) is generated by the user. The public key is shared openly, while the private key remains confidential.

- Sender encrypts a message using the recipient's public key.
- Only the recipient can decrypt the message using their private key.

The security comes from the fact that an eavesdropper will not be able to decipher private key even with a powerful computer. For example, factorizing very large number.

Shor's algorithm which can run on a quantum computer can solve these problems rendering such encryption techniques ineffective. Many companies and governments are working towards post quantum cryptography.

Quantum Communication:

Quantum communication is a cutting-edge technology that uses the principles of quantum mechanics to enable ultra-secure communication. It ensures that data cannot be intercepted or tampered with without detection, making it a powerful tool for secure communication.

It uses principles like Quantum Entanglement and Superposition. For example:

Quantum Key Distribution (QKD):

- A method to securely share encryption keys using quantum states (e.g., photons).
- Photons (light particles) encode quantum states representing the key.
- Keys are exchanged over optical fibers or free-space links (via satellites or ground-based systems).
- Any attempt to intercept the quantum channel alters the quantum state, alerting the sender and receiver.

Strengths of Quantum Communication Over Traditional Communication

- Unbreakable Security
- Detection of Eavesdropping
- Future-Proof Against Quantum Computing
- No Need for Secure Key Storage
- Applications in Critical Sectors such Defense, banking and healthcare.

Challenges of Quantum Communication

- **Signal Loss Over Long Distances:** Quantum signals weaken over long distances in optical fibers, requiring repeaters or satellite-based systems.
- **Quantum Repeaters Are Underdeveloped:** Current technology lacks reliable quantum repeaters to amplify signals without disrupting quantum states.

- **Environmental Sensitivity:** Quantum particles are highly sensitive to environmental disturbances like noise, temperature, and atmospheric interference.
- **High Cost:** Building quantum communication infrastructure (satellites, fiber networks) is expensive.

Quantum Teleportation:

- Quantum teleportation is a process in which the **state of a quantum particle** (e.g., a photon or electron) is transferred from one location to another without physically moving the particle itself.
- While the entanglement itself is instantaneous, quantum teleportation relies on classical communication to transfer measurement results. This classical communication is bound by the speed of light.
- **Thus, it cannot achieve faster than light communication.**

Quantum Sensing and Metrology:

Quantum sensing and metrology leverage the unique properties of quantum mechanics, such as **superposition** and **entanglement** to achieve highly precise measurements of physical quantities.

Measurement Mechanism:

- Quantum systems, like **atoms, photons, or ions**, are highly sensitive to external influences such as magnetic fields, gravitational forces, or temperature changes.
- Changes in these external factors alter the quantum state of the system, which is then measured to infer the underlying physical properties.

Examples of Quantum Sensing and Metrology

1. Atomic Clocks (Time Measurement)

- Use the oscillations of electrons in atoms (like cesium or rubidium) as a highly stable reference for time.
- These oscillations are measured with extreme precision using quantum properties.
- **Applications:**
 - GPS systems require atomic clocks to synchronize signals across satellites.
 - Global timekeeping standards.

2. Quantum Magnetometers (Magnetic Field Detection)

- to measure magnetic fields with high sensitivity.
- **Applications:**
 - Non-invasive brain imaging (magnetoencephalography or MEG).
 - Detection of submarines and mines in defense.

3. Quantum Gravimeters (Gravity Measurement)

- Measure variations in gravitational fields using cold atoms in free fall, taking advantage of quantum interference.
- **Applications:**

- Mineral exploration and oil detection.
- Earthquake prediction and environmental monitoring.

How Normal clocks using Quartz crystal Work?

Quartz clocks are a type of **oscillatory clock** that uses the piezoelectric properties of quartz crystal to keep time accurately.

Piezoelectric Materials and Their Role

- Piezoelectric materials, such as quartz (silicon dioxide), generate an **electric charge** when subjected to mechanical stress.
- Conversely, when an electric field is applied, the material **vibrates mechanically** at a precise frequency. When electricity flows through the quartz, it vibrates at a **natural resonant frequency** (often 32,768 Hz, for clocks). These vibrations are highly stable and consistent over time.
- The high-frequency oscillations are divided by a circuit until they produce one pulse per second.
- These pulses drive the clock's time display, either by:
 - Moving gears in mechanical clocks.
 - Powering an electronic display in digital clocks.

Challenges of Quartz Clocks

- **Temperature Sensitivity:** Quartz oscillation frequency changes slightly with temperature, affecting accuracy.
- **Aging of Crystal:** Over time, the physical properties of the quartz crystal can change, causing drift.
- **Mechanical Limitations:** Moving parts (in mechanical clocks) wear down, impacting precision.

How Atomic Clocks Overcome These Challenges?

Atomic clocks use the **vibration of atoms (cesium-133 and rubidium-87)**, rather than quartz, to measure time with extreme precision. These vibrations are based on quantum transitions between energy states in atoms, which are unaffected by external factors like temperature or aging.

Cesium-133's vibration frequency (9,192,631,770 oscillations per second) defines one second in the **International System of Units (SI)**.

Advantages of Atomic Clocks

- Unmatched Precision
- Temperature Independence
- No Mechanical Wear
- Global Time Standards

More Resources: <https://www.youtube.com/watch?v=OWJCfOvochA>

Here is a brief awareness about Quantum Mechanics, which can totally be skipped.

It's not important for examination and is added here only for curiosity.

Quantum Mechanics: Scientists of late 19th and early 20th century realized that laws of physics which govern the macro world fail to explain the nature at micro scale such as atoms, molecules and subatomic particles. This led to a new branch in physics called Quantum Mechanics.

- The word "quantum" in quantum mechanics refers to the concept of discreteness or individual packets of energy or matter.
- It originates from the Latin word quantus, meaning "how much."
- In the context of physics, it signifies that certain physical properties, such as energy, angular momentum, or charge, are not continuous but instead occur in discrete units or "quanta."

Some Important Names and their contributions:

Planck's Quantum Hypothesis (1900):

- **Max Planck** introduced the idea that energy is quantized.
- Energy is emitted or absorbed in discrete packets called **quanta**.

Einstein's Contribution: Light as Quanta (1905)

- Light behaves as particles, called **photons**, in addition to behaving as waves.
- This explanation of the **photoelectric effect** showed that energy of emitted electrons depends on the frequency of light, not its intensity.
- Established the **particle nature of light** and laid the foundation for the concept of **wave-particle duality**.

De Broglie's Hypothesis: Wave-Particle Duality (1924)

- If light (a wave) can behave as a particle (photon), then particles like electrons can also exhibit wave-like behavior.
- Introduced the concept of wave-particle duality for matter.
- Provided the basis for modern quantum mechanics.

Heisenberg's Uncertainty Principle (1927)

- **Key Idea:** It is impossible to precisely determine both the position and momentum of a particle simultaneously.
- Challenged the deterministic worldview of classical mechanics.
- Suggested that nature has an intrinsic limit to measurement precision.

Schrödinger's equation (1926)

- The behaviour of quantum particles is described by a **wavefunction** which contains all the information about the system.
- When we solve Schrodinger's equation we get probabilities and a very important interpretation is that all those probabilities exist simultaneously.