What is Quantum Communication?

1. What is Quantum Communication?

Quantum communication is the transfer of information using the principles of **quantum mechanics** rather than classical physics.
Instead of sending classical bits (0s and 1s), it often uses **quantum states** (qubits) carried by photons (particles of light).

2. Key Quantum Principles Behind It

- **Superposition**
  A qubit can exist in a combination of $|0\rangle$ and $|1\rangle$ at the same time.
  This allows quantum communication systems to encode more complex information.
- **Entanglement**
  Two or more qubits can be entangled, meaning their states are linked.
  Measuring one immediately determines the other, even if they're far apart.
  → This enables *instantaneous correlations* useful in communication and security.
- **No-Cloning Theorem**
  You cannot copy an unknown quantum state.
  → This makes quantum communication secure, since eavesdropping is detectable.
- **Measurement Collapse**
  When you measure a quantum state, it collapses to $|0\rangle$ or $|1\rangle$.
  → This property is used in security (detecting intruders).

3. How Quantum Communication Works

- **Carriers of Information:** Usually photons transmitted through optical fibers or free space.
- **Encoding Information:**
  Example: Polarization of photons (horizontal = 0, vertical = 1).
- **Transmission:** Sent over quantum channels (fiber optics, satellite-to-ground links).
- **Detection:** Special quantum detectors measure and decode the states.

4. Main Applications

- **Quantum Key Distribution (QKD):**
  Securely sharing encryption keys using quantum states (e.g., BB84 protocol).
  If an eavesdropper tries to intercept, the disturbance reveals their presence.
- **Quantum Networks:**
  Building a "Quantum Internet" where quantum information (qubits) can be sent between distant quantum computers.
- **Quantum Teleportation:**
  Transfer of quantum state information using entanglement and classical communication.
  (Note: Not physical teleportation, only quantum state transfer.)

5. Advantages

Ultra-secure communication (cannot be hacked without detection).
Enables future **quantum internet**.
Can link quantum computers globally.

6. Challenges

Photon loss in optical fibers (long distances).
Decoherence (quantum states easily disturbed by environment).

Need for **quantum repeaters** (devices to extend distance).
Current systems are expensive and complex.

The Major Results

- **QKD (BB84, Ekert protocols):** Practical secure communication.
- **Teleportation:** Trade-off between entanglement and classical communication.
- **Superdense Coding:** Doubles classical capacity per qubit with entanglement.
- **Entanglement Distillation:** Makes reliable long-distance quantum communication possible.
- **Quantum Channel Theory:** Shows surprising new limits and capacities beyond classical communication.

Quantum Key Distribution (QKD) Basics

- **Goal:** Allow two parties (traditionally called **Alice** and **Bob**) to create a shared secret key.
- **Guarantee:** Any eavesdropper (**Eve**) trying to intercept introduces errors that Alice & Bob can detect.
- **Reason it works:**
  - Quantum states cannot be measured without disturbance (**measurement collapse**).
  - Unknown quantum states cannot be copied (**no-cloning theorem**).

How QKD Works (Step-by-Step with BB84 Example)

The **BB84 protocol** (Bennett & Brassard, 1984) is the first and most famous QKD scheme.

1. Photon Preparation

- Alice prepares photons polarized in one of **two bases**:
  - **Rectilinear basis (+):** $|0\rangle$ = horizontal, $|1\rangle$ = vertical
  - **Diagonal basis (×):** $|+\rangle$ = 45°, $|-\rangle$ = 135°

2. Transmission

- Alice sends a random sequence of photons (random basis, random bit).

3. Measurement

- Bob measures each incoming photon in a **random basis** (either + or ×).

4. Sifting

- Alice and Bob publicly announce which basis they used (not the result).
- They keep only the cases where their bases matched → this becomes the **raw key**.

5. Error Checking

- They publicly compare a subset of bits.
- If the error rate is low → Eve was not present.
- If error rate is high → discard communication.

6. Privacy Amplification

- Apply error correction + privacy amplification techniques to ensure a secure final key.

A simplified example of BB84 QKD step by step

Goal

Alice and Bob want to establish a shared **secret key** using quantum states.

We'll walk through **6 photons (bits)** as an example.

1. Alice Prepares & Sends Photons

- Alice wants to send a random string of bits (0s and 1s).
- She chooses **two things for each bit**:
    1. **Bit value (0 or 1)**
    2. **Encoding basis**:
        - **Rectilinear (+ basis):**
            - 0 = Horizontal polarization (→)
            - 1 = Vertical polarization (↑)
        - **Diagonal (× basis):**
            - 0 = 45° polarization (↗)
            - 1 = 135° polarization (↖)

Step	Alice's Basis	Alice's Bit	Photon Sent
1	+	0	Horizontal
2	×	1	135°
3	+	1	Vertical
4	×	0	45°
5	+	0	Horizontal
6	×	1	135°

Physical implementation:

Alice uses a **photon source** (laser attenuated to single photons) + **polarizers** to prepare each photon in the correct polarization.

2. Transmission to Bob

- Alice sends the sequence of photons over a **quantum channel**:
    - Optical fiber
    - Free-space link (satellite → ground)

The photons **carry the quantum states** across the channel.

3. Bob Chooses Random Measurement Bases

- Bob doesn't know Alice's basis, so for each photon he chooses randomly between:
    - **Rectilinear (+ basis)**
    - **Diagonal (× basis)**
- If Bob's basis = Alice's basis → **he gets the correct bit**.
- If Bob's basis ≠ Alice's basis → **his result is random (50% chance)**.

Step	Alice's Basis	Alice's Bit	Bob's Basis	Bob's Result
1	+	0	$0\rangle$	+
2	×	1	$-\rangle$	+
3	+	1	$1\rangle$	×
4	×	0	$+\rangle$	×
5	+	0	$0\rangle$	+
6	×	1	$-\rangle$	×

Physical implementation:
Bob uses a **beam splitter** that randomly directs photons into one of two polarizers (one for +, one for ×), followed by **single-photon detectors**.

4. Sifting Process (Public Discussion)

- After transmission, Alice & Bob communicate over a **classical channel** (like the internet).
- They announce **which basis** they used for each photon (not the bit values!).
- They keep only the cases where they **used the same basis**.
  → This is called **sifting**.

Example:

- Alice: (+, ×, +, ×, +, ×)
- Bob: (+, +, ×, ×, +, ×)
- Keep positions 1, 4, 5, 6.

Step	Alice's Basis	Bob's Basis	Keep?
1	+	+	✓
2	×	+	✗
3	+	×	✗
4	×	×	✓
5	+	+	✓
6	×	×	✓

5. Raw Key

From those matching basis cases:

- Step 1 → 0
- Step 4 → 0
- Step 5 → 0
- Step 6 → 1

Raw Key = **0011** (if Bob measured correctly in step 6).

6. Error Checking

- To check for eavesdroppers (Eve), Alice & Bob publicly compare a **random subset of their results**.
- If Eve tried to measure, she introduces errors (because of measurement disturbance + no-cloning).
- If the error rate is **below threshold (~11%)**, they proceed. Otherwise, they discard and restart.

Alice and Bob randomly reveal a **subset** of their raw key.

- If too many mismatches appear → Eve (the eavesdropper) is present.
- If matches are good → they keep the rest as a **secure key**.

7. Post-Processing

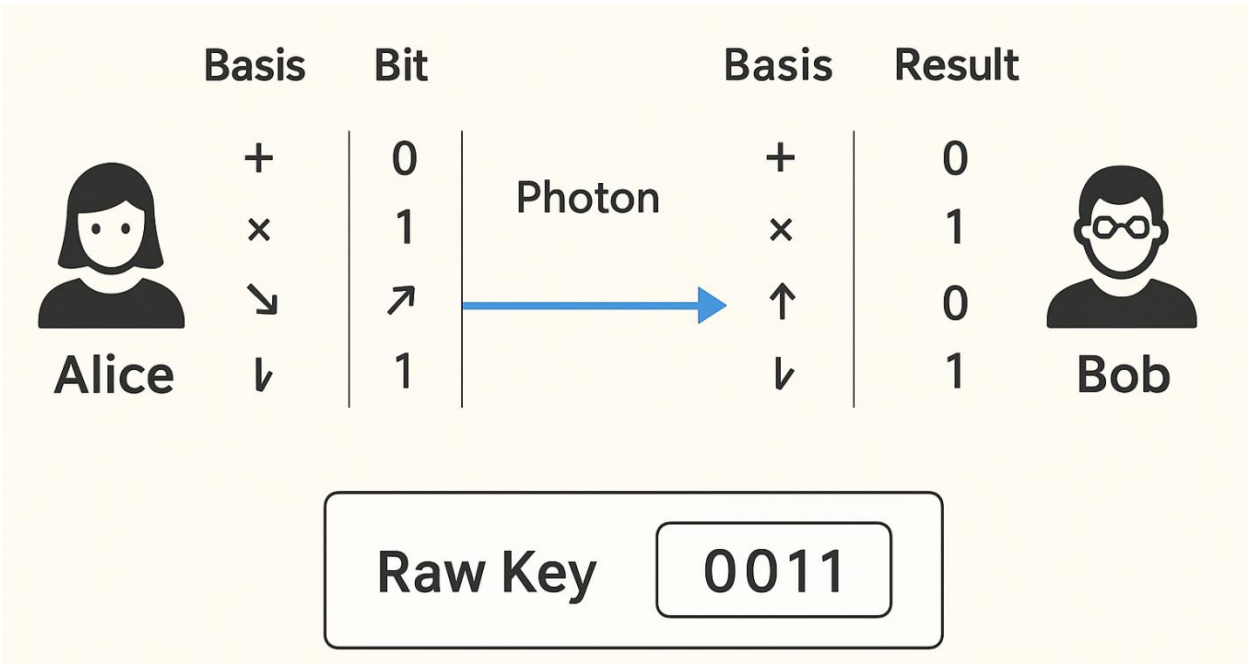
Even without Eve, there may be **channel noise**. To fix this:

1. **Error Correction**
   - Alice & Bob apply classical error-correcting codes to make sure they have **identical keys**.
2. **Privacy Amplification**

- They shorten the key using hash functions to remove any partial knowledge Eve might have.

8. Final Key

After error correction & privacy amplification, they get a **shorter but perfectly secure key**, which they can now use for encryption (e.g., a **one-time pad**)



Summary of Example:

- Alice sends 6 photons → Bob measures.
- They keep only 4 cases with same basis.
- Their shared raw key = **0011**.
- After error checking & privacy amplification → Final secure key.

What is Entanglement?

- Two (or more) particles are **entangled** when their quantum states are correlated in such a way that measuring one **instantly determines** the state of the other, no matter how far apart they are.
- Example: For an entangled pair (EPR pair):

$$|\Phi+\rangle=1/2(|00\rangle+|11\rangle)$$

If Alice measures her qubit as `0`, Bob's qubit is instantly `0`. If Alice measures `1`, Bob's is `1`.

Role of Entanglement in Communication

Entanglement enables communication tasks such as:

1. Quantum Teleportation

- Entanglement allows Alice to send the **state of a qubit** to Bob without physically transmitting the particle.
- Requirements:
  - Alice and Bob share an entangled pair.
  - Alice performs a joint measurement on her entangled qubit + the qubit she wants to send.
  - She sends **2 classical bits** to Bob.
  - Bob applies the right operation to recover the original state.

Result: 1 entangled pair + 2 classical bits → transfer of 1 qubit state.

Example:

Alice wants to send an unknown qubit $|\psi\rangle$|\psi\rangle to Bob.

- They share $|\Phi+\rangle$|\Phi^+\rangle.
- Alice measures her qubits and tells Bob her result (classical 2 bits).
- Bob applies a correction (Pauli operation).
- Bob now has $|\psi\rangle$|\psi\rangle, even though Alice no longer does.

2. Superdense Coding

- Entanglement allows Alice to send **2 classical bits of information by sending only 1 qubit**.
- Process:
  - Alice and Bob share $|\Phi+\rangle$|\Phi^+\rangle.
  - Alice applies one of four operations (I, X, Z, or XZ) on her qubit → changes the joint state into one of four Bell states.
  - She sends her qubit to Bob.
  - Bob performs a Bell-state measurement → learns which operation Alice did → recovers 2 classical bits.

Result: 1 qubit + entanglement = 2 classical bits.

Example:

- Alice wants to send "10" (two classical bits).
- She applies Pauli-X (flip) on her half of the entangled qubit.
- Sends it to Bob.
- Bob measures → sees which Bell state they share → learns "10".

3. Quantum Key Distribution (E91 Protocol)

- Uses entangled pairs to generate secure keys.
- Alice and Bob measure entangled photons in random bases.
- Correlations follow **quantum mechanics**, not classical.

- An eavesdropper cannot copy the entanglement, and interference introduces errors that Alice & Bob detect using **Bell's inequality tests**.

Summary

- **Teleportation:** Send a qubit state using entanglement + classical bits.
- **Superdense Coding:** Double classical capacity using entanglement.
- **QKD (E91):** Generate secure keys via entanglement correlations.

What is the Quantum Internet?

The **Quantum Internet** is a future network that allows devices to **send, receive, and process quantum information (qubits)** across long distances — just like today's internet does with classical bits.

It's not meant to *replace* the classical internet, but to **complement it**, enabling tasks that are impossible with classical networks.

Core Idea

- In the classical internet: Information = **0s and 1s**.
- In the quantum internet: Information = **quantum states (superposition & entanglement)**.
- Quantum Internet will use **entanglement** as the main "link" between nodes, instead of just electromagnetic signals.

Key Building Blocks

1. **Qubits as Information Units**
   - Sent using photons through fiber optics or satellites.
2. **Entanglement Distribution**
   - Distant parties (say Alice in India and Bob in the USA) share entangled qubits.
   - Even across continents, changes in measurement on one qubit affect correlations with the other.
3. **Quantum Repeaters**
   - Like classical repeaters, but they use **entanglement swapping** and **purification** to extend distance.
   - Overcome photon losses in fibers.
4. **Quantum Memories**
   - Store entangled states for later use.

Examples of Quantum Internet Applications

1. Quantum Key Distribution (QKD) on a Global Scale

- Alice and Bob can share a **secret encryption key** across the world.
- Example: A bank in **New York** and a branch in **Tokyo** could exchange secure keys via quantum satellites → impossible to hack.

2. Distributed Quantum Computing

- Multiple small quantum computers could link together over a quantum internet → forming a much more **powerful virtual quantum computer**.
- Example: Two 50-qubit computers in different labs connect and behave like one 100-qubit computer.

3. Quantum Teleportation of Information

- Using entanglement + classical channels, the **quantum state** of a particle can be transmitted across the network.
- Example: A quantum sensor in **Paris** can "teleport" its measured state instantly to a lab in **Tokyo**.

4. Ultra-Precise Synchronization

- Entangled photons can synchronize atomic clocks across the globe with **unprecedented precision**.

- Example: GPS systems could become **1000× more accurate**, useful for navigation and scientific research.

Real-World Progress

- **China's Micius satellite (2017):** Sent entangled photons between two cities 1200 km apart.
- **US DOE Quantum Internet Blueprint (2020):** Plans for a national quantum internet.
- **EU Quantum Communication Infrastructure (EuroQCI):** Aims to build a secure quantum network across Europe.
- **Toshiba & BT UK trials (2022):** QKD links over metropolitan fiber networks.

Simple Analogy

Think of the **classical internet** like sending **copies of a document**. The **quantum internet** is like sharing a **single magical notebook** that both you and your friend have — whatever happens in one instantly affects the other.

What is Secure Global Networking?

It means creating a worldwide communication system where **sensitive information** (banking, defense, healthcare, government, research data, etc.) is **100% secure**, not just "computationally hard to hack."

- **Today's internet security:**
  - Relies on cryptographic algorithms (RSA, ECC).
  - Security depends on the difficulty of solving math problems (like factoring).
  - A powerful **quantum computer** could break these algorithms in the future.
- **Secure networking with quantum communication (QKD):**
  - Security comes from **laws of physics**, not math problems.
  - If anyone tries to eavesdrop, the communication is disturbed and detected.

How International Banking Network Works with Quantum Security

1. Entanglement or QKD Distribution Organizations in different countries generate shared secret keys **with absolute security.**

- Satellites (like China's *Micius*) or undersea fiber optics distribute **entangled photon pairs** or **QKD signals** between global banking hubs.
- Example links:
  - London ↔ New York
  - Singapore ↔ Tokyo
  - Zurich ↔ Frankfurt

2. Secure Key Generation

- Using **BB84 protocol** or **entanglement-based QKD (E91)**, each bank generates a **shared secret key** with its partner.
- If hackers (Eve) try to eavesdrop → errors appear → transmission aborted.
  - 3. **One-Time Pad (OTP) Encryption** These keys can encrypt classical communication (emails, bank transactions, video calls).
- Once a key is shared, the bank uses it to encrypt transaction data with OTP.
- OTP + QKD = **provably unbreakable encryption**.

3. Integration with Classical Networks: Classical internet carries the bulk data, but encryption keys are provided by the **quantum network**.

Example: International Banking Network

Imagine **Bank A (London)** and **Bank B (Singapore)** want to exchange **financial transaction data** securely.

Today's Method

- They use RSA/ECC encryption over classical internet.
- Vulnerable to future quantum computers (Shor's algorithm).
- Hackers could record encrypted data now and **decrypt later** when quantum computers are available.

With Quantum Secure Networking

1. Satellites (like China's **Micius**) distribute **entangled photon pairs** between London and Singapore.
2. Using **QKD (BB84 or E91 protocol)**, the two banks establish a **shared secret key**.
3. Banks use that key for **one-time pad encryption** on transaction data.
4. If hackers try to intercept → disturbance is detected → session aborted.

Result: Transactions remain **secure forever**, even against future quantum computers.

Other Real-World Applications

- **Defense & Government:** Secure communication between military bases or embassies worldwide.
- **Healthcare:** Transferring sensitive patient/genomic data securely across continents.
- **Research:** Sharing experimental results in high-security fields (e.g., nuclear, AI, or pharmaceutical research).
- **Finance:** Global stock exchanges and interbank transfers safe from cyberattacks.

Simple Analogy

Think of today's internet like a **safe with a complex lock** — a stronger thief (quantum computer) could eventually open it.

Quantum secure networking is like a **safe that destroys its contents if someone tampers with it** — so only the true owners can ever use it.

In short: Secure Global Networking with the quantum internet = **absolutely unhackable worldwide communication**, powered by **entanglement + QKD**, protecting data for governments, banks, hospitals, and individuals.

Benefits for International Banking

Future-proof security → safe even against quantum computers.
No risk of "store now, decrypt later" attacks (where hackers record data today to break later).
Tamper detection → banks know instantly if someone tries to spy.
Trustless Security → security is based on physics, not on computational hardness.

Real-World Progress

- **Swiss Bank network**: Using QKD systems from **ID Quantique** for secure communication.
- **China (Micius satellite)**: Demonstrated QKD between Beijing and Vienna → potential model for **international finance QKD networks**.
- **Toshiba & BT UK trials (2022)**: QKD deployed over live metro banking fiber networks in London.
- **European Union EuroQCI Project**: Aiming to connect **European central banks and governments** via quantum-secure channels.