

Real-world application domains:

Healthcare (Drug Discovery)

Drug discovery is a very long and expensive process. To design a new medicine, scientists need to understand how different molecules behave, how they bond with proteins in the human body, and what chemical reactions they may cause. **Classical computers try to simulate these molecules, but the calculations quickly become too complex.** This is because even a small molecule can have many possible electron interactions, and tracking all of them requires enormous computing power.

Quantum computers can handle this better. Molecules are quantum systems themselves, so a quantum



computer can represent them more naturally. This means it can simulate the electronic structure of a molecule — basically, how electrons are arranged and how they interact — more efficiently than classical computers. If scientists can predict these interactions faster and more accurately, they can test fewer compounds in the lab, saving both time and cost.

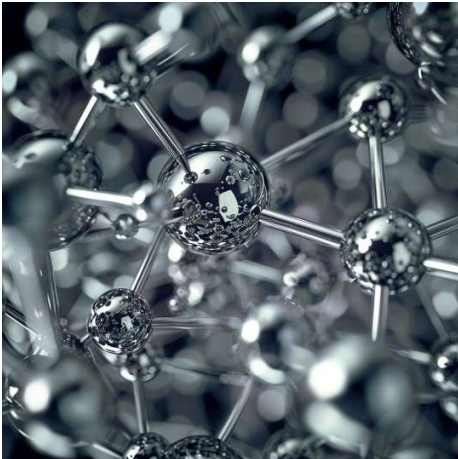
In the short term, researchers use hybrid methods. A common approach is the **Variational Quantum Eigensolver (VQE)**, where a quantum computer is used to represent the molecule, while a classical computer helps optimize the result. This method works well for small molecules or fragments of

proteins.

In the long term, when we have fault-tolerant quantum computers (systems that can run without frequent errors), researchers could simulate very large and complex molecules, such as those used in cancer drugs or vaccines. This would speed up the path from drug discovery to actual treatment, making new medicines available to people much faster.

Material Science

Quantum computers are very useful in material science because they can simulate materials at the quantum level. In many cases, classical computers fail to capture the complex behavior of electrons inside a material. This is especially true when electrons are strongly correlated, meaning the state of one electron strongly depends on the others.



With quantum simulation, scientists can study such complex systems more directly. Some important applications are:

High-temperature superconductors: Quantum simulation may help in discovering new superconducting materials that work at higher temperatures. These materials could allow lossless electricity transmission and revolutionize power grids.

Topological materials: These are special materials with unique surface properties useful in electronics and quantum devices. Quantum computers can help design them by modeling their electronic structures.

Catalysts: Many industrial processes depend on catalysts. By simulating many-body quantum interactions, quantum computers can guide the design of more efficient catalysts, which can save energy and reduce costs.

In short, quantum simulation allows us to look deeper into the “quantum playground” of materials, where the rules are too complex for normal computers. This can lead to new discoveries in energy, electronics, and industry.

Logistics and Optimization

Quantum computing can help solve complex optimization problems in logistics that are very hard for classical computers. These problems usually involve many possibilities to consider at once, like finding the best routes for delivery trucks, scheduling vehicles, or managing supply chains efficiently.

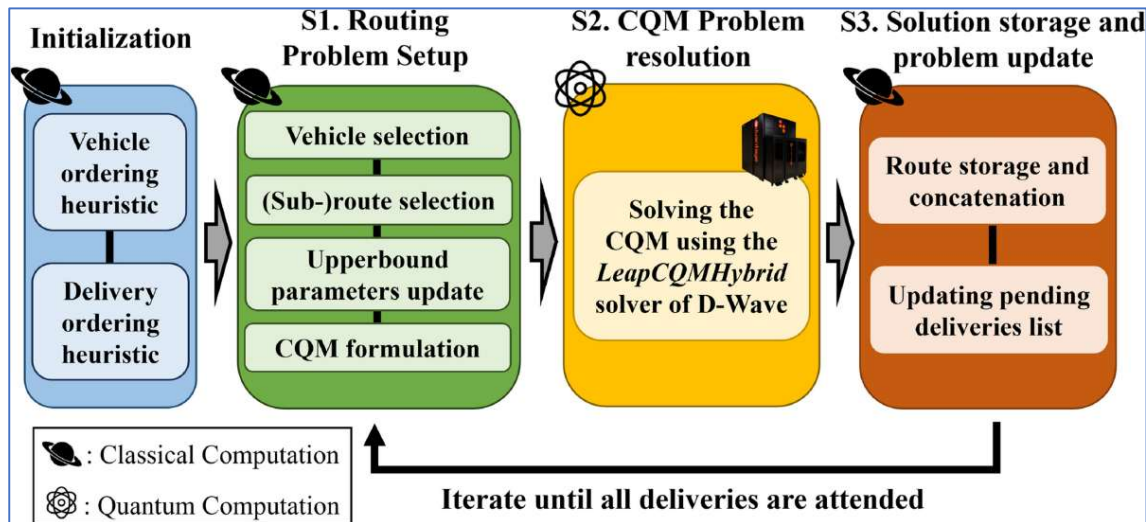
Quantum algorithms, such as **Quantum Approximate Optimization Algorithm (QAOA)** and **quantum annealing**, are designed to handle such combinatorial problems. They explore many possible solutions simultaneously and find the most efficient ones faster than classical methods in some cases.

Even in the near term, before fully powerful quantum computers are available, companies can benefit from **quantum-inspired approaches**. These combine quantum techniques with classical optimization methods in hybrid pipelines. In these pipelines, quantum subroutines perform part of the calculation while classical computers handle the rest.

Some practical use cases include:

- **Routing and vehicle scheduling:** Determining the fastest or most cost-effective routes for delivery fleets.

- **Portfolio optimization:** Choosing the best combination of investments for maximum returns with minimal risk.
- **Supply-chain resiliency:** Finding the most reliable and efficient paths for goods, even when disruptions occur.



The above figure shows a step-by-step process for solving a delivery problem using a mix of classical and quantum computing.

1. Initialization (Problem Setup):

- The process starts by setting up the problem. This involves using two heuristics (smart guesses):
 - One for ordering vehicles.
 - Another for ordering deliveries.
- This step uses classical computing (regular computers).

2. S1. Routing Problem Setup:

- Next, the system selects vehicles and decides on sub-routes (smaller parts of the delivery routes).
- It also updates upperbound parameters (limits to guide the solution) and creates a CQM (Constrained Quadratic Model) formulation.
- This step also uses classical computing.

3. S2. CQM Problem Resolution:

- This is where quantum computing comes in. The CQM problem is solved using a special tool called LeapCQMHybrid solver from D-Wave.
- The solver finds the best way to handle the delivery routes.

- This step combines quantum and classical computing.

4. S3. Solution Storage and Problem Update:

- The solved routes are stored and combined (concatenated) into a complete plan.
- The list of pending deliveries (those still needing attention) is updated.
- This step uses classical computing.

5. Iteration:

- The whole process repeats (loops back) until all deliveries are taken care of.
- The line at the bottom shows the division between classical computing (left side) and quantum computing (middle quantum symbol).

So, this method uses regular computers to set up and organize the delivery problem, quantum computing to solve the tricky parts, and then regular computers again to store and update the solution, repeating until everything is delivered!

Quantum Sensing and Precision Timing

Quantum sensors are special devices that use the unique properties of quantum mechanics—like **coherence** and **entanglement**—to measure things with extremely high precision, much better than classical sensors.

Some common types of quantum sensors are:

- **Atomic clocks:** These measure time very accurately. They are important for telecom networks, GPS systems, and financial transactions where precise timing matters.
- **Magnetometers:** These detect tiny magnetic fields. They can be used in medical imaging, like detecting signals from the brain or heart.
- **Interferometric sensors:** These measure small changes in distance or motion, useful in geological surveys, navigation, and detecting gravitational waves.

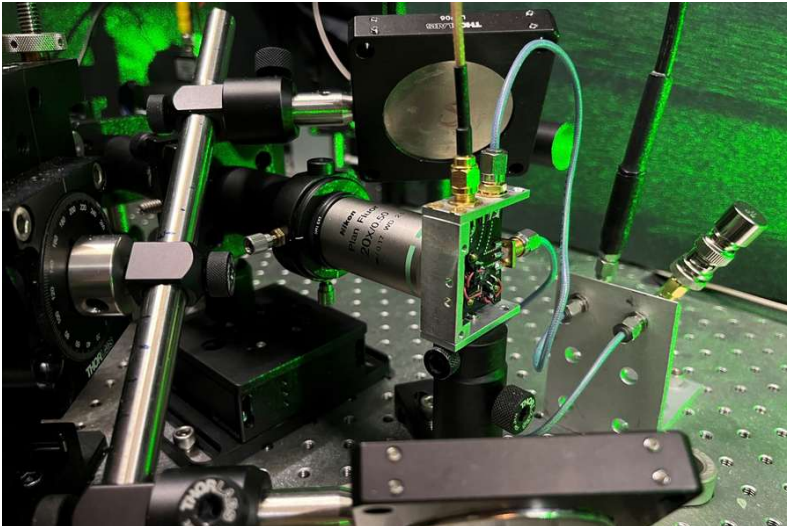


Fig: Quantum sensor can detect electromagnetic signals of any frequency

Practical applications include:

- **Navigation:** Quantum sensors can improve GPS accuracy and work even in places where GPS signals are weak.
- **Medical imaging:** They enhance imaging techniques to detect finer details in tissues or organs.
- **Geological surveying:** They help map underground resources or detect changes in the Earth's structure.
- **Timekeeping:** Extremely precise clocks are critical for telecom networks, financial systems, and scientific research.

In short, quantum sensing lets us measure things that were previously too small or subtle to detect, opening the door to better navigation, medicine, and science.

Industrial Case Studies:

Several big tech companies are actively exploring quantum computing and running real-world experiments across different industries like **pharmaceuticals, materials, and optimization**.

1. IBM

- **Focus:** IBM works on **superconducting qubits** and building large-scale quantum computers.
- **Cloud Access:** They provide access to quantum computers via **IBM Quantum Cloud**, so anyone can run experiments online.
- **Applications:** They collaborate with companies in **pharma, materials, and finance** to test real-world problems.
- **Hybrid Workflows:** IBM often uses a mix of **quantum and classical computers** to solve complex problems efficiently.
- **Research & Tools:** IBM provides **Qiskit**, an open-source software platform for building quantum algorithms.

Example: IBM helped pharmaceutical companies simulate small molecules to discover new drugs faster.

2. Google

- **Focus:** Google works on **superconducting qubits** and building **large-scale quantum chips**.
- **Hardware Research:** They focus on creating more **powerful and reliable quantum processors**.
- **Quantum Supremacy:** Google demonstrated that a quantum computer could solve a problem faster than the world's fastest classical supercomputer in specific tasks.

- **Applications:** Their work is mostly in **research and benchmarking algorithms**, but it can eventually help in **optimization, chemistry, and materials science**.
- **Tools & Ecosystem:** Google provides tools like **Cirq**, a software platform to develop and test quantum algorithms.

Example: Google tested a quantum algorithm that solved a calculation in minutes which would take thousands of years on a classical computer.

3. PsiQuantum

- **Focus:** PsiQuantum uses **photonic qubits**—qubits made of light particles.
- **Scalability:** Their goal is to build **large, manufacturable quantum computers** using high-volume photonic chips.
- **Applications:** They aim to solve **real-world problems** in areas like **optimization, materials, and chemistry**.
- **Approach:** Unlike superconducting or trapped-ion qubits, photonic qubits can be easier to **scale up** and work at **room temperature**.
- **Roadmap:** They plan to produce **millions of photonic qubits** for industrial-level quantum computing.

Example: PsiQuantum's photonic technology can potentially handle huge computations faster and more reliably than current small-scale quantum computers.

4. Microsoft

- **Focus:** Microsoft works on **trapped-ion and topological qubits**, which are different types of qubits designed for **stability and error resistance**.
- **Cloud Access:** They provide **Azure Quantum**, a platform for developers to access quantum hardware and software.
- **Software Tools:** Microsoft offers **Q#**, a programming language for creating quantum algorithms.
- **Applications:** Their focus is on **optimization, materials, chemistry, and finance**. They also collaborate with industry partners to test quantum solutions.
- **Ecosystem Approach:** Microsoft combines **hardware, software, and cloud services** to make quantum computing accessible for businesses and researchers.

Example: Microsoft helps companies run hybrid quantum-classical algorithms to find optimal solutions for supply chains or material design.

Ethical, Societal, and Policy Considerations in Quantum Technology

Quantum technology has the potential to solve extremely complex problems in science, medicine, finance, and security. But with this power come serious **ethical, societal, and policy challenges** that must be addressed carefully.

1. Cryptography and Data Privacy

- Most of today's secure communication, like online banking, emails, and cloud storage, relies on **asymmetric encryption** (methods like RSA).
- A powerful quantum computer could break some of these encryption methods, putting **sensitive personal and corporate data at risk**.
- This creates an urgent need for **post-quantum cryptography**—new encryption methods that can resist attacks from quantum computers.

2. Dual-Use and Military Applications

- Quantum technology is **dual-use**, meaning it can be used for both peaceful and military purposes.
- Applications in military or intelligence could include **quantum-enhanced surveillance, secure communication for defense, or new kinds of weapons systems**.
- Without proper regulation, quantum tech could increase **geopolitical tensions** or lead to misuse.

3. Workforce and Inequality Issues

- Quantum technology is highly specialized and expensive to develop.
- Countries or companies with access to advanced quantum tech could gain **significant economic and strategic advantages**.
- This may create **unequal benefits**, leaving other countries, small companies, or communities behind.

4. Policy and Governance Responses

To manage these risks, governments and organizations are taking several measures:

- **Post-quantum cryptography:** Developing encryption methods that remain safe in the quantum era.

- **Export controls and regulations:** Limiting the transfer of sensitive quantum technology to prevent misuse.
- **Standards and international collaboration:** Creating global guidelines for safe, ethical, and responsible development.
- **Public-private research governance:** Encouraging transparency and collaboration between governments, academia, and private companies.

5. Education and Public Awareness

- Educating scientists, engineers, policymakers, and the public about quantum technology is essential.
- Open and transparent discussions help ensure that **society can benefit from quantum advances fairly** and that ethical concerns are addressed proactively.

So, finally, Quantum technology is extremely powerful, but it can **break current security, be misused for military purposes, and create inequality**. To handle these issues, society needs **better laws, safe encryption, education, and international cooperation**.

Challenges to Adoption of Quantum Technology

Quantum technology is promising, but adopting it widely faces several challenges:

1. High Costs

- Quantum computers need **expensive hardware** like superconducting circuits, lasers, or photonic chips.
- Many systems require **cryogenic cooling** (very low temperatures), which adds to both **capital costs** (buying equipment) and **operating costs** (running and maintaining it).

2. Lack of Skilled Workforce

- There are very few **quantum engineers, algorithm developers, and researchers** compared to the growing demand.
- Quantum computing requires **cross-disciplinary knowledge** in physics, computer science, and mathematics, making it harder to find and train talent.

3. Immature Standards

- Quantum hardware and software **standards are not yet fully developed**.

- Different quantum computers use **different architectures, languages, and interfaces**, making it difficult to compare performance or run programs across platforms.

4. Integration with Classical Systems

- Most quantum computers still work alongside **classical computers**.
- Integrating quantum systems into **existing IT infrastructure** is complex and requires new tools and software workflows.

Ways to Overcome These Challenges

- **Targeted Funding:** Governments and companies can provide grants and incentives for quantum research and infrastructure.
- **Standardized Benchmarks:** Developing clear benchmarks and performance metrics helps in comparing different quantum systems.
- **Cross-Disciplinary Education:** Universities can create courses combining physics, computer science, and engineering to train more quantum professionals.
- **Open Toolchains:** Providing open-source software and development platforms lowers the barrier for new researchers and startups to enter the field.

Hence, Quantum technology is expensive, needs special skills, and lacks standardization. Solving these problems needs **funding, education, open tools, and shared standards** so more people and companies can use it.

Emerging Careers in Quantum Technology

Quantum technology is creating many **new career opportunities**. These roles require a mix of **quantum knowledge, programming skills, and domain expertise**.

1. Key Roles

- **Quantum Algorithm Developer:** Designs quantum algorithms to solve problems in optimization, chemistry, finance, etc.
- **Quantum Hardware Engineer:** Works on building and maintaining quantum machines, including cryogenics and chip fabrication.
- **Quantum Software Engineer:** Programs quantum computers using platforms like **Qiskit** (IBM) or **Cirq** (Google).

- **Quantum Applications Scientist:** Domain expert who applies quantum methods to **real-world problems** in areas like medicine, materials, or logistics.
- **Quantum Product Manager:** Coordinates **quantum projects**, bridging technical teams and business goals.

2. Core Skills Needed

- **Mathematics:** Linear algebra and basic quantum mechanics.
- **Programming:** Python is widely used for quantum software.
- **Hardware Awareness:** Understanding hardware constraints like qubit errors and connectivity.
- **Domain Knowledge:** Specialized knowledge in fields like chemistry, finance, optimization, or sensing helps in applying quantum solutions.

3. Preparation Pathways

- **University Degrees:** Courses in physics, computer science, and quantum electives.
- **Online Specializations:** Platforms offering quantum computing courses and hands-on labs.
- **Internships:** Work with **quantum startups, labs, or industry partners** to gain practical experience.
- **Hackathons & Benchmarks:** Participate in coding competitions and challenges to **build skills and reputation**.

In short, Quantum technology offers **exciting careers** in programming, hardware, research, and product management. Success requires a mix of **math, quantum basics, coding, and domain expertise**. Practical experience through **courses, internships, and hackathons** can help you enter this field.

Educational and Research Landscape in Quantum Technology

Quantum technology is growing fast, and so are **education and research opportunities**. Universities, national labs, and industry are creating programs to train the next generation of quantum professionals.

1. Education and Curriculum

- Universities are designing courses that mix **quantum theory, hardware labs, and software programming**.

- Students can **practice on real quantum computers** via **cloud platforms** like IBM Quantum and Google Cirq.
- **Open-source frameworks** like Qiskit (IBM) and Cirq (Google) help learners **experiment and build quantum programs** easily.

2. Research Landscape

- Research in quantum technology is **highly interdisciplinary**:
 - **Physics**: Understanding qubits and quantum mechanics.
 - **Materials science**: Developing better qubit materials and chips.
 - **Computer Science**: Programming, algorithms, and software platforms.
 - **Domain sciences**: Applying quantum methods to chemistry, biology, finance, and logistics.
- Labs and universities often work with **industry partners and consortia** to align research with real-world applications.

3. Public Resources and Use-Case Catalogs

- There are **public datasets, tutorials, and case studies** that show how quantum can be applied in industries.
- These help researchers **focus on practical problems** and accelerate the **research-to-application pathway**.

Finally, Education and research in quantum computing combine **theory, hardware, software, and applications**. Open-source tools, cloud access, and interdisciplinary research make it easier for students and researchers to **learn, experiment, and solve real-world problems**.

India's Opportunity in the Global Quantum Race

Quantum technology is becoming one of the most important areas of science and industry worldwide. Countries like the USA, China, and some European nations are investing heavily in quantum research, development, and industry. India, with its strong scientific community and growing technology ecosystem, also has a strategic opportunity to join this global race.

The **National Quantum Mission (NQM)** is India's key initiative in this area. It is a multi-year program with significant government funding and several specialized research hubs. The mission has three main goals:

1. **Boost Research and Innovation** – Fund universities and labs to develop new quantum technologies and explore innovative applications.
2. **Develop Skills and Manufacturing Ecosystem** – Train engineers, scientists, and technicians in quantum technologies and create infrastructure for manufacturing quantum hardware like photonics chips and sensors.
3. **Promote Startups and Public–Private Partnerships** – Support new quantum startups, encourage collaboration between industry and research labs, and turn research into commercial products.

India has several strengths that make this possible:

- **Large STEM Talent Pool** – India produces a huge number of science, technology, engineering, and mathematics graduates every year, providing the human resources needed for advanced quantum research.
- **Growing Startup Ecosystem** – Indian startups are increasingly working on cutting-edge technologies, making it possible to translate research into products quickly.
- **Government Support** – With funding through NQM and other programs, India can invest in both research and practical applications.

India can focus on **niche areas** where it can quickly become competitive:

- **Quantum Software Development** – Writing programs and algorithms that run on quantum computers.
- **Applications in Agriculture and Healthcare** – Using quantum computing and quantum sensing for better crop yields, drug discovery, and precision medicine.
- **Scalable Manufacturing for Photonics and Sensors** – Producing components needed for quantum computers and sensors efficiently.

To fully succeed, India will need **coordinated efforts**: strong government policy, collaboration between industry and research institutions, and specialized skill-development programs. If these are in place, India can turn its research and talent into **real commercial products**, compete globally, and become a major player in the quantum technology revolution.

*** The End***