LTI
Let's Solve

IIT MADRAS

Quantum Computing

A Larsen & Toubro Group Company

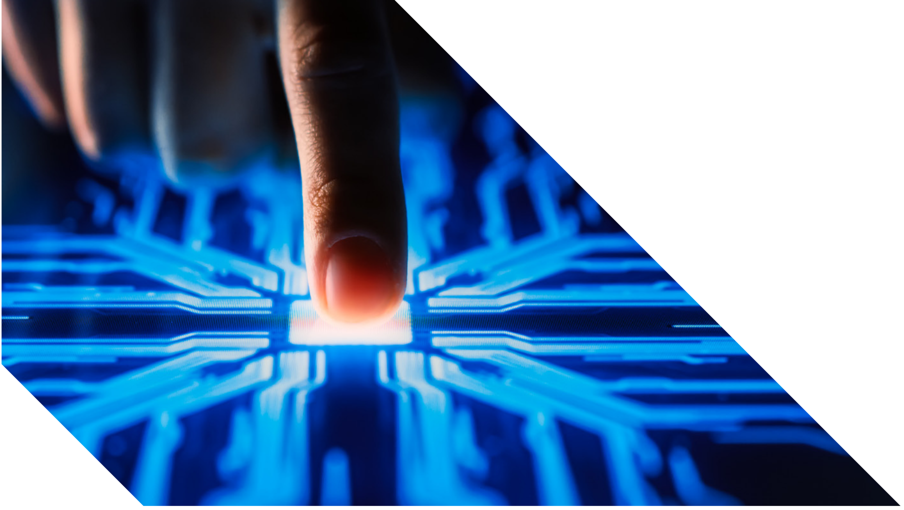
Table of **Contents**

Introduction

Early computing devices were made from electronic calculators developed using transistors. These electronic calculators used a binary number system based on the integers '0' and '1', commonly known as bits (binary digits).

Arithmetic devices gradually evolved to perform more complex mathematical calculations, resulting in the advent of classical computers. The power and performance of these computers have continuously increased over time, resulting in many technologies like mobile phones, the internet, and so on. Due to the intrinsic size restrictions of transistors, we are currently approaching a point when the limits of our computing capabilities will meet saturation. This, in turn, will impose a ceiling on the capabilities of classical computers.

Inspired by Prof. Richard Feynman's lecture on **"Simulating Physics with Computers,"** the scientific community began developing computers using quantum physics principles. The quantum systems are inherently dual in nature, which means they behave as a particle and have a wave nature. The wave nature causes the quantum systems to exhibit features like superposition and entanglement. In superposition, the particles can simultaneously be in two different positions.



Paul Benioff pioneered the pro-computers basic model for a quantum computer. The first working prototype of a quantum computer was demonstrated at Oxford University. It was a two-qubit quantum computer made using liquid Nuclear Magnetic Resonance (NMR) qubits, which carried out a simple search algorithm. This was followed by several successful demonstrations of quantum computers based on different technological platforms like NMR qubits, Nitrogen-Vacancy qubits, ion-trap quantum computers, and superconducting qubits with an increasing number of qubits. Currently, several quantum computers have been built by private enterprises like IBM, Google, IonQ, Honeywell, Xanadu, PsiQuantum, and so on.

In classical computing, operating with bits, the algorithm is executed step-by-step, while superposition in Quantum Computing allows the execution of several parts of the algorithm simultaneously. This property of inheriting multiple states simultaneously gives quantum computers tremendous power over classical computers. Quantum Computing is thus a new technology that leverages the laws of quantum mechanics to provide exponential improvement in performance which may be of use in new areas of computing.

The hardware component in the quantum computer should be used in conjunction with software that is compatible with it. This means that in addition to hardware development, we should also focus on developing algorithms that can use quantum properties to their advantage. Such algorithms are called quantum algorithms. Several algorithms, such as the Deutsch algorithm, Shor's algorithm, Grover's algorithm, and others, have proven quantum advantage in current quantum computers. However, these are only a few algorithms, and research into developing additional algorithms that may utilize quantum properties and execution on a quantum computer is underway.

Many industrial analysts call the current decade the Quantum decade, where the enterprises will start seeing business value from Quantum Computing. IBM is the pioneer on providing hardware and software and others are also rapidly developing the Quantum Computing building blocks. However, with advances, these services will soon be cheaper, bringing up revolutionary opportunities for businesses. Before we go into the future of Quantum Computing, let's first establish specific facts about it.

Fact 1

Quantum computers are made up of quantum bits, aka qubits. Unlike a regular computer bit, which can be 0 or 1, a qubit can be either of those or a superposition of both 0 and 1.

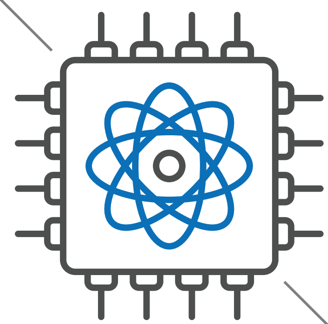
Fact 2

Quantum Computing devices will handle information more fundamentally than "classical" devices like smartphones, laptops, or even today's most powerful supercomputers. It solves problems faster than classical devices. It operates on the quantum state of subatomic particles.

Fact 3

Quantum computers are not intended to replace classical computers; they are expected to be a different tool to be used on top of classical computers to support high-speed computations or processing, which classical computers will take decades or centuries to accomplish. Enterprises will use it to solve complex problems beyond a classical computer's capabilities.

Quantum Computing and the solutions it will bring are poised to bring a revolution to the industry. It can provide critical breakthroughs in areas like AI, Machine Learning, Cryptography, Optimization, etc. Gartner rates Quantum Computing as the decade's most disruptive technology and believes that 40% of large enterprises are planning to create initiatives around Quantum Computing by 2025.



What is
Quantum Computing?

Quantum computers are fundamentally different from classical computers. Although both try to solve problems, they manipulate data differently. In classical computing, operations are performed using binary bits. This means the bits are either 0 or 1, true or false, positive or negative. However, in Quantum Computing, the bit is referred to as a quantum bit or qubit, which can exhibit multiple states simultaneously.

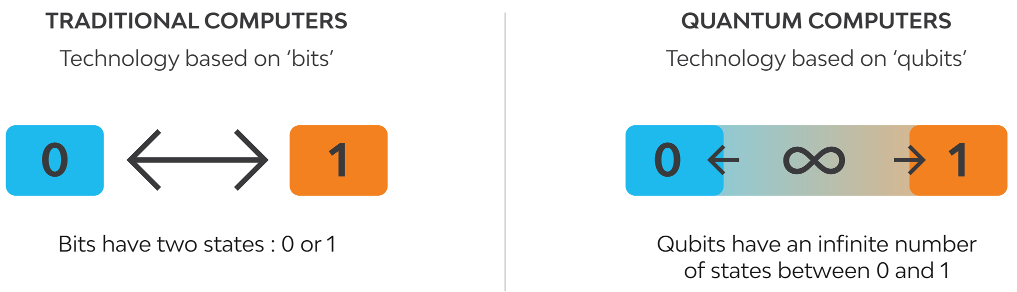
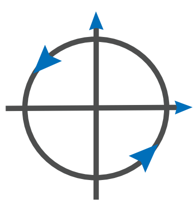


Fig. 1 : Traditional Computers vs. Quantum Computers
(Source: Australian Academy of Science)

Quantum computers are constructed based on the principles of quantum mechanics, such as Superposition, Entanglement, and Interference. These are crucial for their operations and make them unique.

Principles of **Quantum Computing**

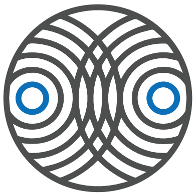


Superposition

Superposition allows a quantum computer to be in multiple states simultaneously. It's based on the counterintuitive ability of a quantum object, like an electron, to exist in multiple states simultaneously. For an electron, one of these states may be the lowest energy level in an atom, while another may be at an excited level. With electrons, in qubits, 0 and 1 simply correspond to states like the lower and upper energy levels. It has some probability of being in the 0 state and some probability of being in the 1 state, unlike classical bits, which must always be in the 0 or 1 states, qubits by their ability to be in superpositions with varying probabilities that quantum operations can manipulate during computations.

Entanglement

Quantum Computing chips are developed with many qubits. These qubits can be entangled together during operation. 'Entanglement' is a phenomenon in which the measurement is not connected ,physically; that is qubit influences the output of another qubit. A measurement on one member of an entangled pair will immediately determine measurements on its partner. A quantum computer leverages entanglement between qubits and the probabilities associated with superpositions to carry out a series of operations (a quantum algorithm) such that certain probabilities are enhanced (i.e., those of the right answers) and others depressed, even to zero (i.e., those of the wrong answers). When a measurement is made at the end of the computation, the probability of measuring the correct response should be maximized.



Interference

Apart from Superposition and Entanglement, another phenomenon at the core of Quantum Computing is 'Interference.'. The qubits are represented in waveforms by wavefunctions. When the qubits are entangled, their wave functions are added together, which creates an overall wave function and produces a constructive or destructive interference.

The firms that have developed quantum hardware also face many challenges in doing so. Since Quantum Computing is still in its early stages, scientists and researchers are working on developing stable hardware. Qubits are based on quantum particles like photons, electrons, ions, atoms, etc. They also interact with the outside environment, which introduces errors in the quantum computer and hence are not fault-tolerant.

The challenges that are currently faced in developing stable hardware are:

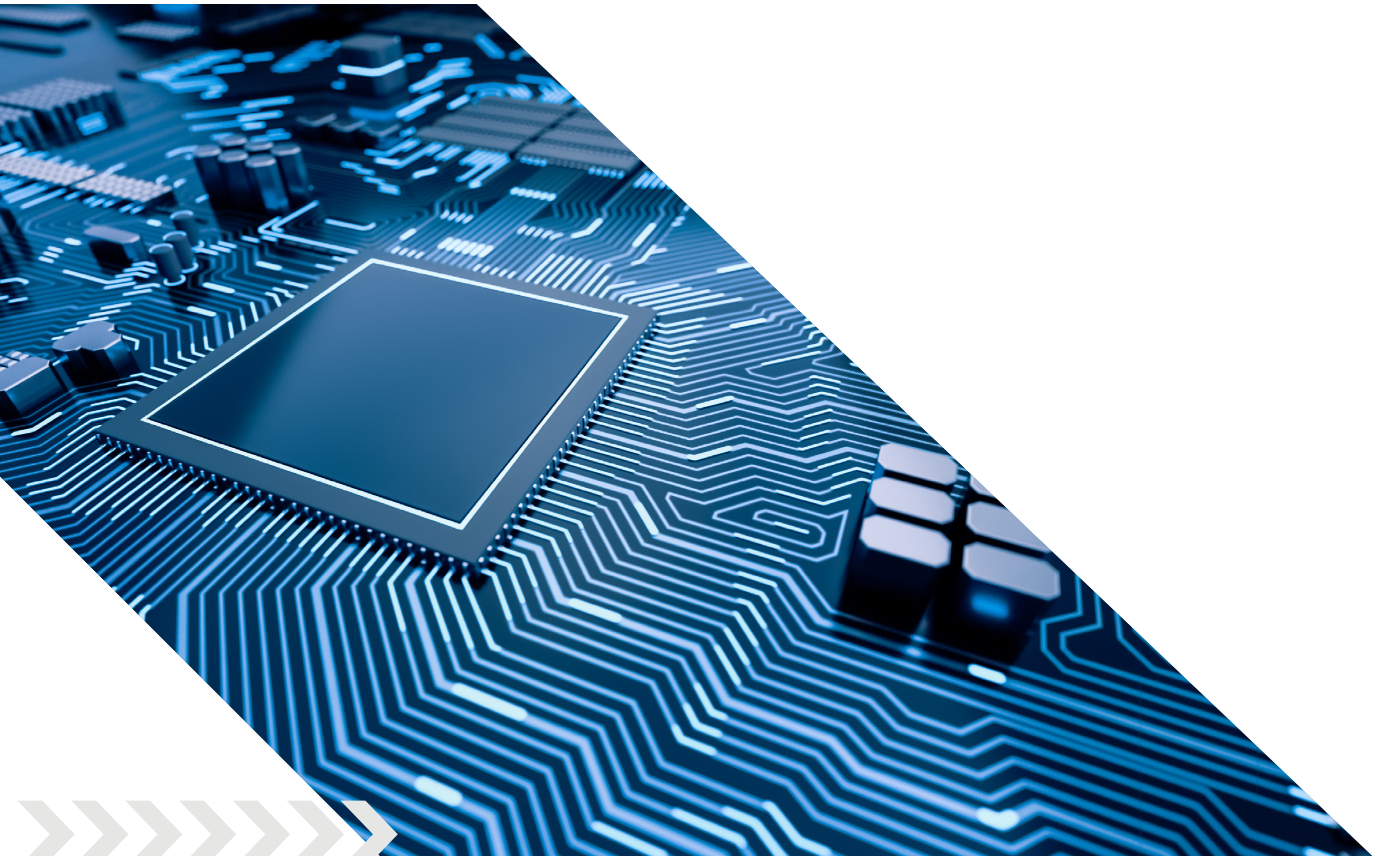
Decoherence The Quantum Bits are entangled which each other, but sometimes they interact with the external environment, which degrades the qubit because of noise. This feature is known as decoherence. In constructing a quantum computer, one critical challenge is shielding the qubits from the noise due to the external environment.

Noise Particles, radiation, heat, and cosmic rays are examples of Noise from which the qubits need to be protected.

Quantum Error Correction Is using many entangled physical qubits to make one Noise-free logical qubit. Currently, enterprises are working on creating fault-tolerant qubits. Many physical qubits are combined to develop fault-tolerant logical qubits. It is estimated that up to 1000 physical qubits could be required to create logical qubits depending on the error correction scheme.

Scalability Scaling quantum computers, i.e., adding more qubits, is also a massive engineering problem, so there is ongoing research in this area as well. Classical Computers vs. Quantum Computers.

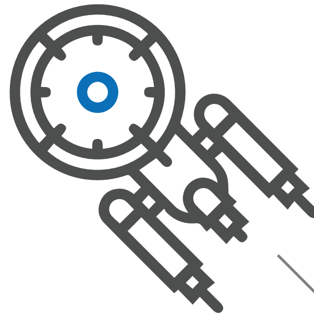
Though current quantum computers are too small to outperform usual (classical) computers for practical applications, they are believed to be capable of solving some computational issues, such as integer factorization (which underlies RSA encryption), faster than classical computers. In theory, a quantum computer with 300 qubits entirely dedicated to computing could perform more calculations in an instant than there are atoms in the visible universe.



Classical Computers vs **Quantum Computers**

Feature	Classical Computer	Quantum Computer
Measurement	Calculates with transistors, which can represent either 0 or 1	Calculates with Qubits which can represent 0 or 1 at the same time
Power	Power increases as the number of transistor increases. Linear increase	Power increases exponentially in proposition to the number of Qubits
Computing	Logical operations	Unitary operations Conditions of atoms
Temperature	Operates at room temperatures, and the error rate is less	Operates at very low temperatures, and error rates are high
Usage	Everyday processing	Optimization problems, data analysis, simulation
Computation	N bit processor = 1 operation	N qubit processor = 2 power N operations
Storage	N bit storage holds 1 value from 0 to 2 power (n-1)	N qubit storage holds 2 power N operations
Gates	Truth table (true/false) Most Gates run forward	Unitary matrix Gates are reversible
Security	Less secure Encryption is based on mathematical algorithms	More secured Encryption is based on Quantum properties

Table 1: Difference between Classical and Quantum Computers (Source: Analytics Insight)



Should Enterprises **care about Quantum Computing?**

Innovation is the key to the future, and with a continuously evolving technology horizon breakthroughs happening across all fields, it becomes essential for an organization to evaluate the impact of technological development on the business and operations and make strategic choices to harness the power of these new technological developments.

In today's connected world, technology has become ubiquitous right from targeted ads, privacy through encryption, booking a taxi, or figuring out what a black hole looks like. All this is made possible with the computing power of the devices surrounding us. Computation technologies have come a long way from first-generation vacuum tube computers sizing as long as 100ft to fitting at the tip of our finger and far more capable than first-generation computers. But with the growing technology consumption, computers need to be more capable than what they are today.

Each day on Earth, we generate 500 million tweets, 294 billion emails, 4 million gigabytes of Facebook data, 65 billion WhatsApp messages, and 720,000 hours of new content added daily on YouTube. In 2018, the total amount of data created, captured, copied, and consumed worldwide was 33 zettabytes (ZB) – equivalent to 33 trillion gigabytes. This grew to 59 ZB in 2020 and is predicted to reach a mind-boggling 175 ZB by 2025. One Zetta Byte is 8,000,000,000,000,000,000,000 bits.

ML algorithms today are limited by the computational power of classical computers. Quantum Computing can administer large data sets at much faster speeds and supply data to AI technologies to analyze data at a more granular level and identify patterns and anomalies. Quantum Computing can also help integrate data by running comparisons between schemes to quickly analyze and understand the relationship between two counterparts.

Need for **an alternative**

The computing industry gained momentum when the first integrated circuits came into the picture 40 years ago. With that, Gordon E. Moore also devised a thumb rule stating that every two years, computers will be twice as capable as the present ones. Moore made this observation by working within the industry and following the trend on the size of transistors. The basic unit in electronic gadgets is getting smaller and smaller. Since then, manufacturers have shown intense competition wishing to keep up with Moore's law, a general benchmark in the industry. This has led to better design tools and demand for better products.

The smallest commercial transistors scale up to just 14 nanometers. For manufacturers, keeping up with Moore's law would imply that they either produce even smaller transistors by overcoming the physical limitation of atoms or by increasing the current transistors' capability to produce smaller transistors means beyond a specific limit, the quantum effects would come in play. Increasing the computing power of the current chip would mean we need to look beyond traditional computing.

There are 4 types of problems that Quantum Computing can solve

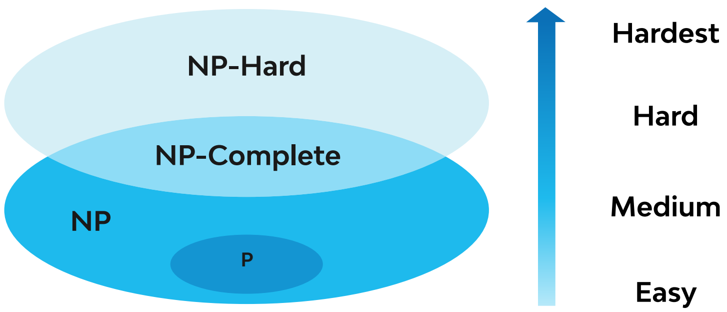


Fig. 2: Types of Problems (Source: Baeldung)

Polynomial (P) : problems are quick to solve

- All basic mathematical operations; addition, subtraction, division, multiplication
- Testing for primacy
- Hash table lookup, string operations, sorting problems
- Shortest Path Algorithms; Djikstra, Bellman-Ford, Floyd-Warshall
- Linear and Binary Search Algorithms for a given set of numbers

Non-Deterministic Polynomial (NP) : problems are quick to verify but slow to solve

- Integer Factorization and
- Graph Isomorphism

Non-Deterministic Polynomial Complete (NP-complete) : problems are also quick to verify, slow to solve, and can be reduced to any other problem

- Traveling Salesman
- Knapsack, and
- Graph Coloring

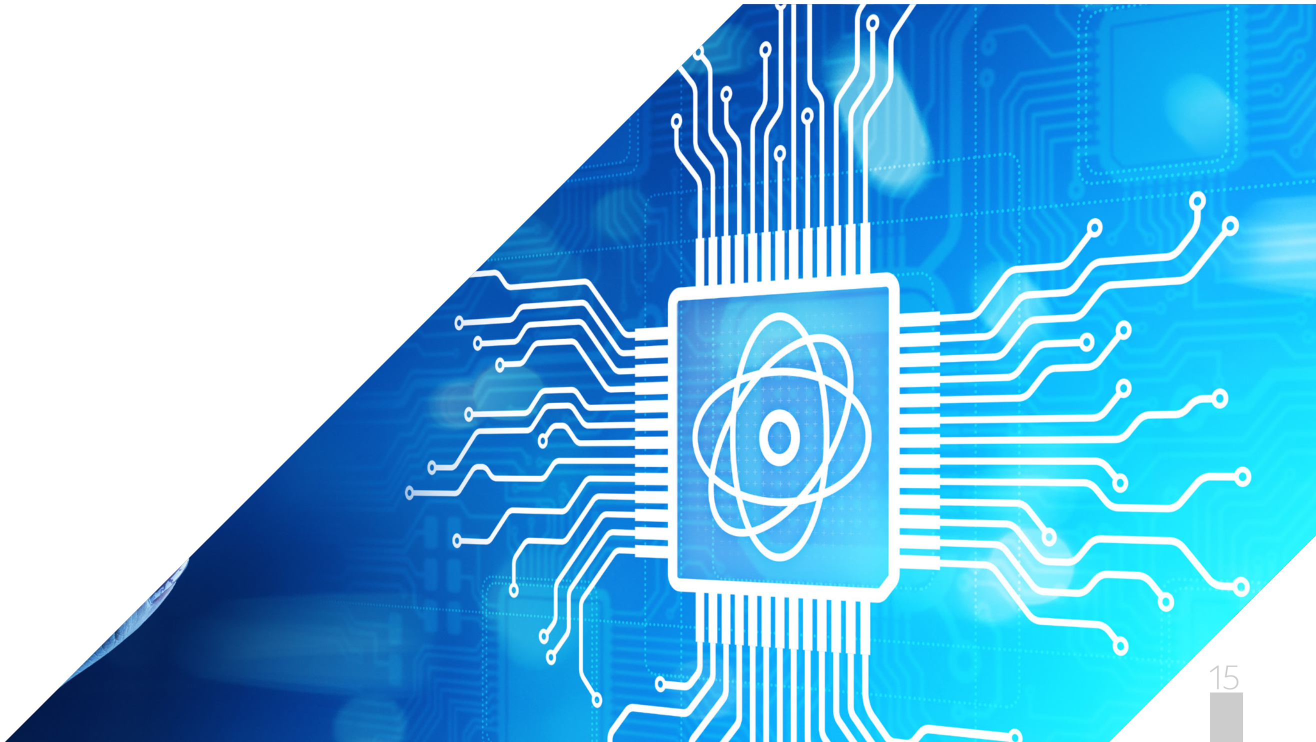
Non-Deterministic Polynomial hard (NP-hard) : problems are slow to verify, slow to solve, and can be reduced to any other problem

- K-means Clustering
- Traveling Salesman Problem, and
- Graph Coloring

‘P’ problems can be solved in a polynomial amount of time, like searching a database for an item. However, when the search space size grows, it becomes a challenging solution even for P problems. P problems are the problems whose solution, if known, can be verified in a polynomial amount of time. Factorization of prime numbers, which is an NP problem, took an exponential amount of time when solved using the classical computer. At the same time, Shor’s Quantum Computing algorithm computes it in polynomial time.

The power of **Qubits could be exploited in the future to come up with solutions for NP-complete problems** in the future.

Although the quantum computers available today are noisy and may take a decade to become mainstream, enterprises should start working on their Quantum Computing business use case and watch out for the developments as the hardware will soon follow. Tech giants are promising quantum computers with 1 million qubits by the decade’s end. Quantum Computing can fundamentally change computation and how our systems are designed in a larger sense.



Forecast for **Quantum Computing Technology**

Quantum Computing is one of the fastest-growing technologies of this decade and is predicted to have one of the highest market potential.

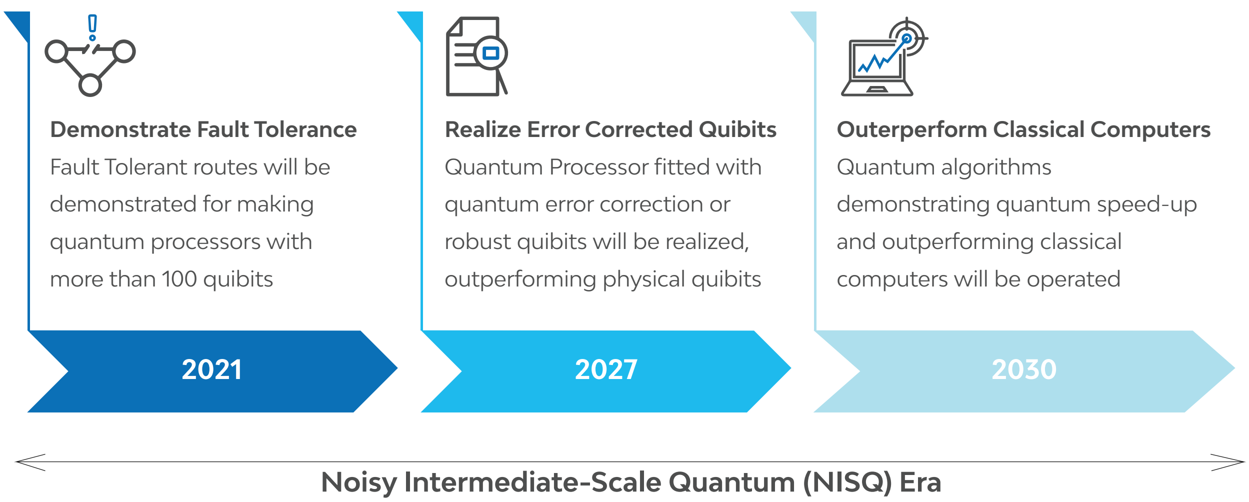


Fig. 3: Forecast for Quantum Computing (Source: Quantum Flagship)

We are currently in the Noisy Intermediate-Scale Quantum (NISQ) era, where the number of qubits is small (100-150 qubits) and lack error correction to perform complex computations but is large enough to demonstrate the quantum advantage. In 2021, IBM unveiled its 127-qubit, Eagle quantum computer. They are the first to break the 100-qubit barrier mark.

Research and development into practical commercial applications of noisy intermediate-scale quantum (NISQ) computers is an issue of immediate urgency for the field. The results of this work will profoundly impact the rate of development of large-scale quantum computers andthe size and robustness of a commercial market for quantum computers.

Although the technology is still nascent, enterprises have started experimenting with different use cases. In collaboration with Avasant Research, the figure below from NASSCOM gives a glimpse of Quantum Computing applications that enterprises with a time horizon look upon.

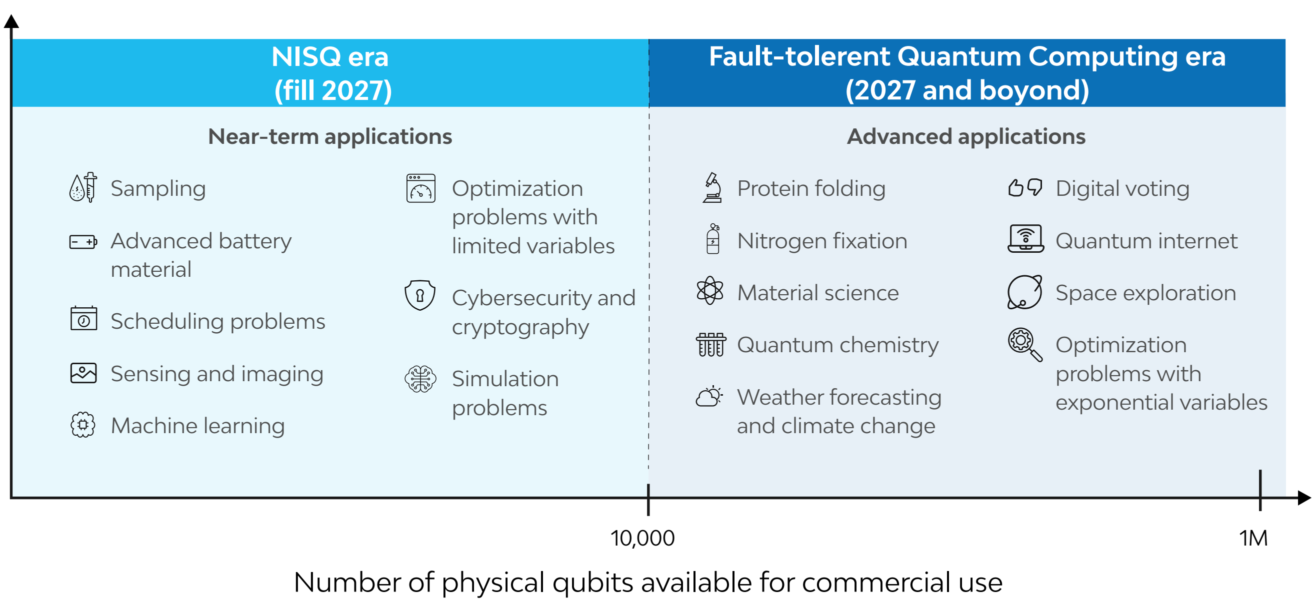


Fig. 4: Applications of Quantum Computers in the NISQ Era and Beyond
(Source: Nasscom + Avasant Research)

LTI
Let's Solve

Market **Overview**

Quantum Computing still may be a nascent technology, but by gaining a perspective on the market potential and opportunity horizon, enterprises can foresee where Quantum Computing is going to have an impact.

According to the Boston Consulting Group (BCG), in the next 3 to 5 years, Quantum Computers manufacturers will generate $5 billion – $10 billion of revenues. Currently, some of the leading full-stack quantum hardware players are Google AI, IBM, D-Wave Systems, Xanadu, and Alibaba Quantum Labs. Full-stack players are hardware manufacturers and provide software development kits to work on the hardware. IonQ, which develops general-purpose Quantum Computing systems, became the first publicly traded Quantum Computing enterprise in 2021, with an estimated initial valuation of $2 billion.

IDC projects customer spend for Quantum Computing to grow from $412 million in 2020 to $8.6 billion in 2027. This represents a 6-year compound annual growth rate (CAGR) of 50.9% over the 2021-2027 forecast period. The forecast includes core Quantum Computing as a service as well as enabling and adjacent Quantum Computing as a service.

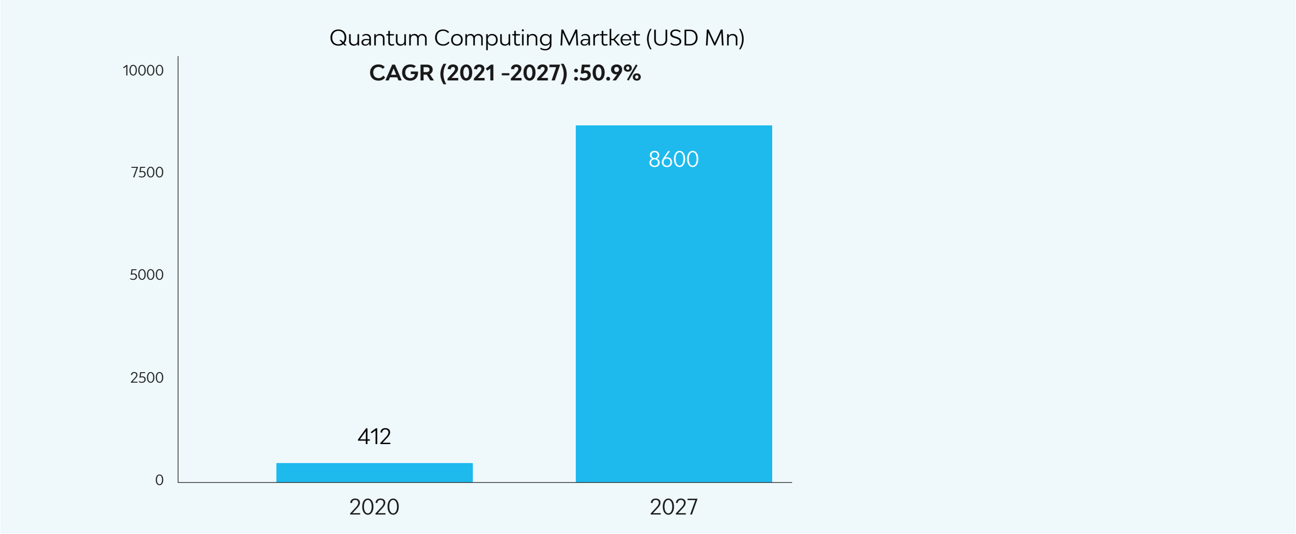


Fig. 5 : Quantum Computing Market CAGR (Source: IDC forecast)

According to Pitchbook data, VCs globally invested more into the Quantum Computing industry in 2021 than combined in the previous three years .Although the technology may not be ready, and may take some time to outperform traditional computers, investors are betting that real-life applications will emerge sooner.

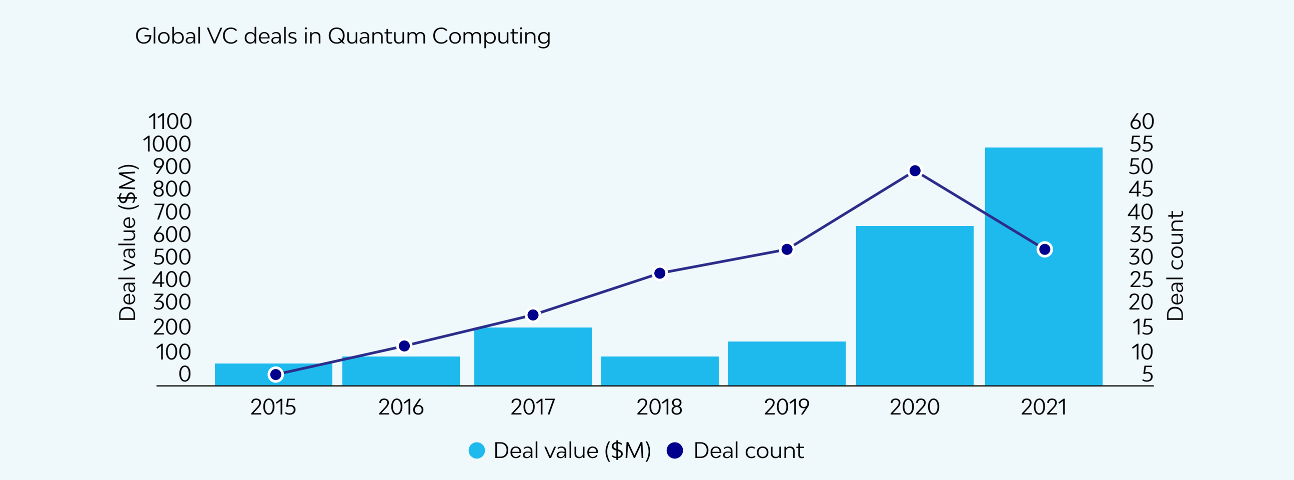


Fig. 6: VC Deals in Quantum Computing (Source: PitchBook)

China and European Union lead significantly in funding for Quantum Computing investment. The below chart shows investments in Quantum Computing across different countries in USD billion.

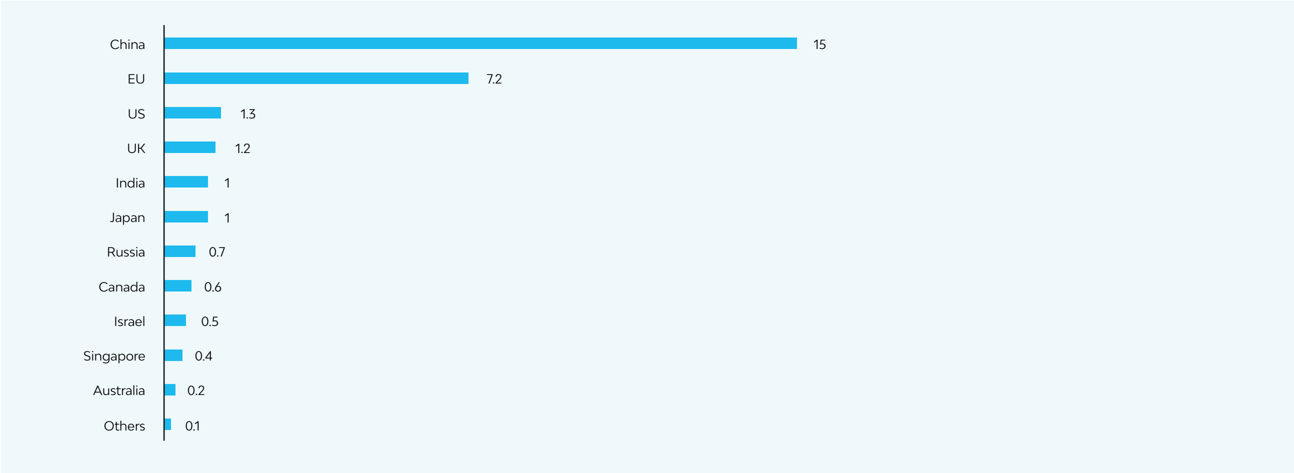


Fig. 7: Investments in Quantum Computing across geographies
(Source: Analytics India Magazine Pvt Ltd)

Governments across the geographies are spending on R&D of Quantum Computing. China is leading the spend on Quantum Computing, it has more patents than the US and the EU. Using Quantum Communication, they have created an ultra-secure data link between two ground stations separated by more than 1,000 miles.

Within the EU, the University of Innsbruck in Austria, has built a 24-qubit prototype of a Quantum computer, which is available online to interested parties, individuals, and corporates. This compact computer's low power consumption of only 1.5 kilowatts is a notable feature. The German government also has announced that it would spend a billion euros to support the development of the country's first Quantum computer. Elsewhere, France and the Netherlands have signed an MoU to collaborate in the R&D of quantum technologies, joining the race to build high-performance supercomputers.

The Government of India has set in motion programs such as Quantum Enabled Science and Technology (QuST) and the National Mission on Quantum Technologies and Applications (NMQTA), leading the development of institutions and projects. Under the NMQTA program, India has a 5-to-7-year goal of developing about 25,000 human resources across software, hardware, and allied tech. The Government has planned an outlay of 1 billion dollars to advance progress in various fields of quantum technologies. It has also planned to develop a 50-qubit quantum computer by 2026.

Corporates are also showing interest in quantum computing. BCG believes 3 factors are driving the interest.

- **Technical Achievement –** More Hyperscalers and Start-ups achieving Quantum Supremacy for e.g. Google.
- **Timeline Clarity –** The technology providers now have a clear roadmap with milestones set along the path to quantum advantage.
- **Use Case Development –** Businesses have started exploring and defining practical use cases for the technology.

Quantum Computing can create value between $450 billion to $850 billion in the next 15 to 30 years. BCG estimates that quantum optimization applications in finance, logistics, and aerospace alone could generate up to $220 billion in annual revenue once the Quantum Computing technology matures.

The following table shows the value creation potential for Quantum Computing across different areas and the range of value in priority use cases once the technology is mature.

Applications		Value Creation Potential ($B)	
		Low	High
Crytography	Encryption/Decryption	$40	$80
Optimization	**Aerospace :** Flight route optimization	$20	$50
	Finance : Portfolio Optimization	$20	$50
	Finance : Risk Management	$10	$20
	Logistics : Vehicle Routing/Network Optimization	$50	$100
Machine Learning	**Automotive :** Automated Vehicle, AI algorithms	$0	$10
	Finance : Fraud and money-laundering prevention	$20	$30
	High Tech : Search & Ads Optimization	$50	$100
	Other: Varied AI applications	$80	$80
Simulation	**Aerospace :** Computational Fluid Dynamics	$10	$20
	Aerospace : Materials development	$10	$20
	Automotive : Computational Fluid Dynamics	$0	$10
	Automotive : Materials and Structural Design	$10	$15
	Chemistry : Catalyst and Enzyme Design	$20	$50
	Energy : Solar Conversion	$10	$30
	Finance : Market Simulation	$20	$35
	High tech : Battery Design	$20	$40
	Manufacturing : Materials Design	$20	$30
	Pharma : Drug discovery and development	$40	$80

Table 2: Potential value creation areas (Source: BCG)

Quantum
Computing Use Cases

Industries have started experimenting with different Quantum Computing use cases. The following figure shows other industries in the Quantum Computing technology adoption lifecycle.

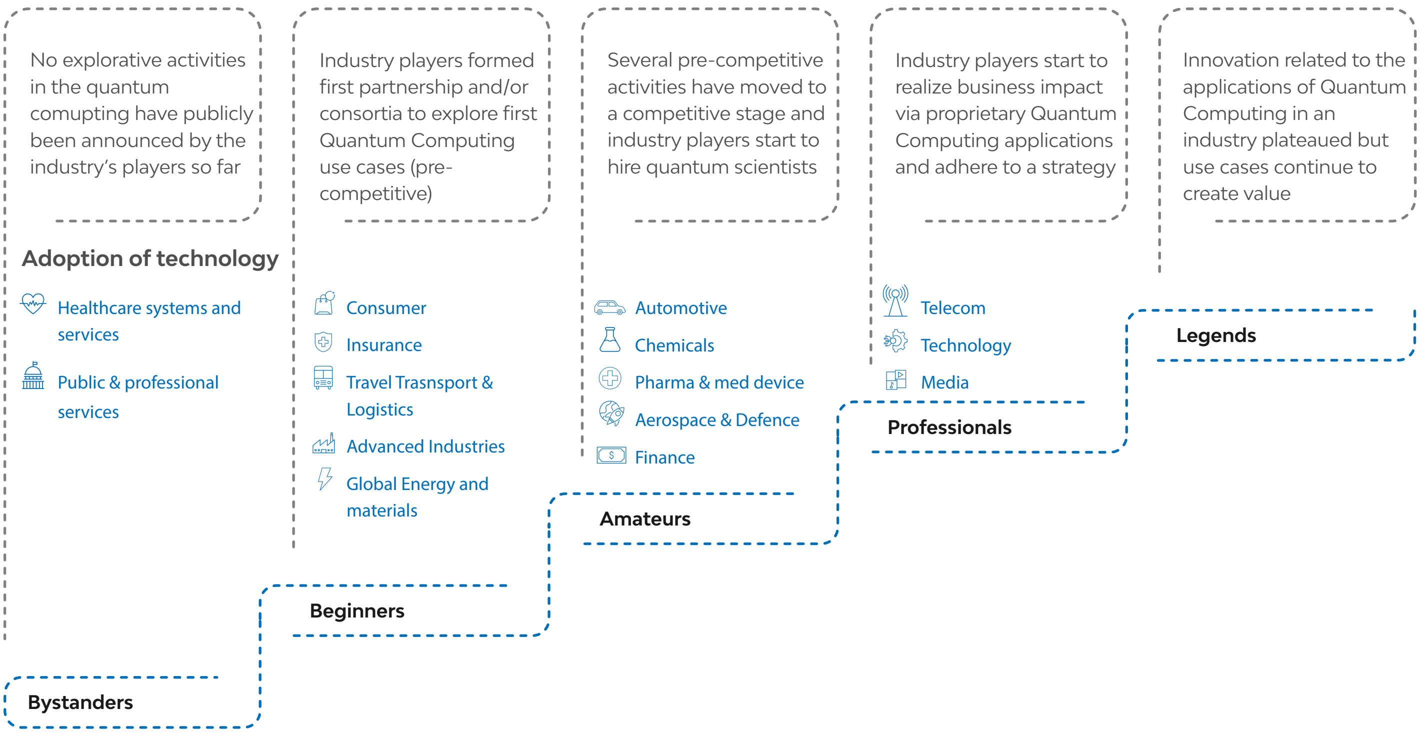


Fig. 8: Industries across Quantum Computing adoption lifecycle (Source: McKinsey)

According to a survey by McKinsey - technology, media, and telecom enterprises have made several breakthroughs over the past five years. Advances include achieving quantum supremacy, developing an industrial quantum computer, and setting up cloud-based quantum-computing services. Some of the most popular industry use cases are elaborated below.

Pharma

Faster R&D : R&D can happen much faster, more precise and targeted, less dependent on trial and error, and more efficient.

Drug development : Quantum Computing simulations can help in molecular comparison in drug development. They can replace laboratory experiments and save on costs.

Cancer treatment by analyzing genetic data : Cambridge Quantum, a research partner of Roche and Crownbio, is developing a Quantum Computing technology to analyze of genetic data for cancer treatment.

Chemicals

Material Discovery and Development : Chemical and biological engineering involve manipulating molecules and subatomic particles, which means it requires quantum mechanics. Through Quantum Computing, chemical reactions can be simulated and help predict the properties of new molecules.

Improve Catalyst Design : Quantum Computing can be used in production to improve catalyst designs. The improved catalyst could enable energy savings in production processes and help replace petrochemicals with more sustainable feedstock.

Manufacturing

Identify process failures : Quantum Computing can help identify which part of the manufacturing process contributed to incidents of product failure by analyzing large manufacturing data sets on operational failures.

Design optimization (e.g., batteries, chips, vehicles, etc.) : Daimler works with IBM's Quantum Computing technology for longer-lasting chips

Communications

Network optimization : Network optimization problems can be modeled and solved using Quantum computers.

Secure Communication : Communication-based on quantum cryptography qualifies as highly secure and impossible to wiretap or intercept.

Insurance

Valuation of instruments, and premiums in complex cases : Enterprises plan to use Quantum computers for data-intensive tasks such as identifying health anomalies.

Accurately simulating weather systems : Catastrophe modeling used in property insurance can be significantly improved through accurate weather simulation using Quantum Computing systems. This benefits the process of pricing, reserving, and settling policy limits. Modeling other aggregate risks such as supply chain interruption, liability risks, or cyber, could also benefit from Quantum Computing capabilities.

Automation of claims : Quantum Computing can automate the claims function in real-time using rapid data flow from smart devices, reducing costs and increasing efficiency.

Improved customer relationship management (CRM) : Quantum Computing can more accurately target customers and predict their preferences based on customer behavior data. This can enhance customer satisfaction and retention by targeting policy holders with more pre-emptive insurance products and service recommendations.

Finance

Risk analysis : Quantum Computing can be used for developing risk classification models.

Portfolio optimization : Quantum computers can be used for Portfolio Optimization; as per a pilot by KPMG, they found that Quantum Computing performed better than any other benchmarking method for near-term investments.

Fraud detection : In 2022, PayPal partnered with IBM to use Quantum Computing in fraud detection.

Financial Forecasting : Accurate forecasts can be made through machine learning based on quantum computers.

Customer Identification (and Assessment) : Quantum Computing may be beneficial improve Financial Supply Chain Efficiency in procurement and payment, focusing on customers and suppliers to increase reduce working capital levels, enhance liquidity, minimize risk, and avoid late payments (47% of suppliers are paid late).

Energy

Utilization prediction : Quantum Computing can be used for energy usage optimization.

Grid optimization : The U.S. Department of Energy (DOE) has two labs established specifically for integrating Quantum Computing into grid optimization.

Weather forecasting : IBM uses Quantum Computing for precise weather forecasting, currently serving almost all consumer tech providers like Apple, Amazon, Google, and Facebook.

Automotive

Reduce manufacturing cost : Quantum computers can help decrease manufacturing processes-related costs and shorten the cycle times by optimizing elements.

Optimizing large autonomous fleets : Volkswagen has partnered with Google to use Quantum Computing for their autonomous vehicle design.

Simulations : Automotive manufacturers can simulate component interactions inside complex hardware systems, calculating system loads, load pathways, noise, and vibration more accurately and thoroughly. This can help in improving costs without losing overall system performance.

Logistics

Route and traffic optimization : Enterprises have partnered with Quantum Computing enterprises into research traffic prediction and optimization.

Knapsack Problem : The knapsack problem is a packing problem aiming to determine the optimal collection of items minimizing the weight of all items and maximizing the value. It has many applications in supply chain management (e.g., truck loading, airplane loading, and lot sizing). A key objective of industry is to increase the customizability and flexibility of production.

How can Enterprises **build Quantum Computing capability?**

Quantum Computing has applications in various use cases across industries. Building a capability in Quantum Computing can open many possibilities for a services-based enterprise. It will enable organizations to easily solve business problems for their clients, such as simulation and optimization, which are currently much harder for classical computers to solve.

Organizations need to focus on 4 key areas to build a Quantum Computing capability

- Hardware
- Software
- Simulators
- Talent

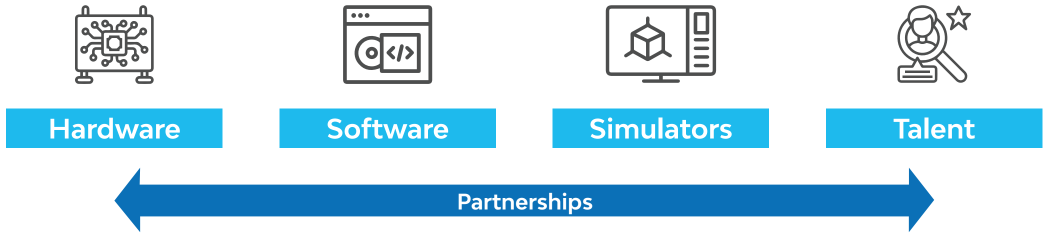


Fig. 9: Levers for building Quantum Computing capability

As Quantum Computing is still a developing field, there is an ongoing research on building the best hardware and most efficient algorithms. Some technology firms have invested considerably in building the hardware, such as Google, IBM, and many start-ups such as Rigetti, D-Wave, etc. Enterprises can partner with these firms to access the hardware over the cloud and start building algorithms.

Some of these firms also offer development kits and have created programming languages of their own for writing programs on quantum hardware. Additionally, some firms provide quantum simulators that run on classical computers. Enterprises can test their algorithms and programs on these simulators before running them on Quantum computers. To train its talent, enterprises can partner with research institutes and universities which are active in this space.

The subsequent sections will cover each of these areas, starting with hardware.

Different Vendors for accessing Quantum Computing Hardware

Currently, there exist technology firms that offer access to their quantum hardware to enterprises on a variety of terms.

IBM

They are one of the most advanced enterprises in this space. They are a full-stack Quantum Computing services provider. They provide access to their quantum hardware and have developed programming languages and libraries to help write programs on their hardware. IBM's quantum processors are made up of superconducting qubits, which are made from superconducting materials such as Niobium and Aluminum, patterned on a Silicon substrate.

Enterprises partner with IBM and become a part of their Q-Network, which has 170 members; who access IBM's Quantum Computing hardware. Their most significant quantum computer is Eagle which has a 127-qubit processor. They also offer a free 5-qubit quantum computer over the cloud for free for anyone to access and experiment with. IT Services enterprise Capgemini has tied up with IBM for accessing their hardware and developing its Quantum Computing lab.

Google

Google has their own Quantum AI lab where they have developed their superconducting quantum computer. Currently, they have a 53-qubit quantum computer, with which they solved a factorization problem in 2019 and declared quantum supremacy. They also offer access to enterprises to their Quantum Computing hardware over the cloud.

D-Wave

Their quantum computers are implemented using the Quantum Annealing model. Quantum Annealing is also implemented using superconducting qubits, but they follow a different computation model and are uniquely designed for optimization and probabilistic sampling problems. Their hardware is accessible via the cloud through cloud providers such as Amazon Braket and QC Ware. Apart from their hardware, they also offer software, developer tools, and services to enable the building of real applications.

Amazon Braket

They are a cloud provider that provides access to other firms' quantum computers. They provide access to Rigetti, IonQ, and D-Wave quantum computers. They also offer development kits for enabling programming on Quantum Computing hardware. Indian IT Services major Infosys has partnered with Amazon to offer Quantum Computing services to its clients.

Microsoft Azure Quantum Platform

They also provide access to other firms' quantum computers. They provide access to Honeywell, IonQ, and QCI-developed quantum computers.

These are some of the vendors that provide access to their Quantum Computing hardware. But to write programs and algorithms, enterprises also require programming tools and access to programming languages to write the code. Various vendors offer that.

Provider	Model	Implementation	Cloud Offerings	Access To	Hyperscaler / QPU
Amazon Basket	Multiple	Multiple	Yes	D-Wave, IonQ, Rigetti	Hyperscaler
Microsoft Azure	Multiple	Multiple	Yes	Honeywell, IonQ, QCI	Hyperscaler
IBM	Gate	Superconducting	Yes	Own System	QPU
Google	Gate	Superconducting	Yes	Own System	QPU
D-Wave	Annealer	Superconducting	Yes	Own System	QPU
Xanadu	Gate	Photonics	Yes	Own System	QPU
Rigetti	Gate	Superconducting	Yes	Own System	QPU

Table 3: Quantum Computing Hardware Providers (Source : Data- The Quantum Insider)

Vendors for providing **Software, Programming tools, and Simulators**

Organizations can choose from various vendors which who offer Quantum Computing services and cloud programming tools. These vendors produce solutions using Quantum Computing per the users' needs.

IBM

Their IBM Quantum Experience offering allows users to drag and drop logic gates (operations) to create their own circuits in a web browser. These circuits can be run remotely on a quantum computer. They have developed Qiskit, an open-source SDK based on Python, enabling users to program the hardware. They also offer Qiskit Runtime, an execution environment to run circuits, and store programs so that other users could use them as a service.

Microsoft QDK

As part of their Quantum Development Kit, Microsoft has developed a high-level programming language Q# for programming on Quantum hardware. Their development kit is open-source and is based on Azure. It enables users to program algorithms for optimization problems, which can be run on simulators or Quantum Computing hardware, to which Microsoft provides access.

Google Cirq

Google has also developed an open-source python library for building quantum circuits, which can be run on its hardware or on quantum simulators.

Rigetti Forest

This is a cloud computing platform offered by the start-up Rigetti, which builds superconducting quantum computers. Through this cloud platform, users can access Rigetti's Quantum Computing hardware.

These are some software providers organizations can partner with to develop their Quantum Computing capability. Instead of directly building programs and algorithms for actual Quantum Computing hardware, organizations can first experiment with Quantum Computing simulators that run on classical computers.

Quantum **Computing Simulators**

Simulators allow users to prototype quantum circuits and algorithms, and explore their performance. Several vendors have quantum simulators as their offerings.

PASQAL They offer 200-Qubit simulators for users to build and test their quantum algorithms.

QuEra They offer 256 Qubit Simulators.

QSim The Ministry of Electronics and Information Technology (MeitY), under the Indian Government, has in 2021 launched the country's first Quantum computer Simulator (QSim) toolkit. This is being executed collaboratively by IISC Bangalore, IIT Roorkee, and C-DAC with the support of MeitY.

Strange To use Quantum Algorithms in Java, one can download and use Strange, an open-source Java quantum computer simulator. With Strange, one can simulate a quantum algorithm by creating several qubits and applying several quantum gates to them.

Partnerships with **Universities and Research Labs**

Many universities have, in cooperation with industries, founded research labs. They help in training the talent and may also partner with enterprises to develop capabilities, solutions and co-inventions for example IIT-Madras who are leading such initiatives.

LTI
Let's Solve

Envisaged **Risks**

Although Quantum Computing will add immense value to technology and the economy, it also comes with some risks. For any organization to consider incubating Quantum Computing as a capability, it would have to consider the below factors.

Here are some of the significant risks that Quantum Computing would introduce :

- There is a high cost associated with building Quantum Computing capability
- There would be a delayed Return on Investment as there is low awareness of near-term applications of Quantum Computing
- Currently, there is a lack of commercially viable use cases as the infrastructure is still developing
- Quantum Computing requires the development of highly specialized and interdisciplinary skills. There is currently a lack of talent and skills, in coding and managing the infrastructure. Developing talent with knowledge in computer science, Quantum Computing, and business acumen, is very critical
- Customers would have other digital technologies a priority
- There is a lack of a proven method to estimate the business impact, which could hinder long-term investments
- There is a lack of application-centered benchmarks, so users cannot easily infer the performance they expect from proposed solutions
- Although the hardware can be accessed through Cloud Service Providers, the availability and scale are often limited, thus limiting research and industrialization activities
- A virtuous demand and supply cycle is critical to establishing a new market. Due to the long-term nature of Quantum Computing, market creation is a challenge

Conclusion

The present constraints of Quantum Computing should not deter enterprises from looking at the potential to address critical issues and establish new businesses. Quantum Computing represents a breakthrough for some difficult operations, and current technological advancement will likely create hybrid cloud architecture through the orchestration of bits (classical), qubits (quantum), and neurons (AI-assisted programming).

Scaling might remain a persistent issue, but new application areas will emerge over the next decade. Low-cost quantum devices, such as quantum random number generators, which can detect unexpected quantum events and turn them into a stream of binary digits, may experience tremendous growth in the next few years.

Random numbers play critical roles in various applications, including quantum communication, cryptography applications such as essential creation, key wrapping and authentication, scientific simulations, and fundamental physics investigations. Developing quantum computer that is fault-tolerant and capable of managing millions of qubits is a long journey. Still, it now is the perfect opportunity to form relationships with suppliers and develop in-house Quantum Computing capabilities. Identifying pilot initiatives for when Quantum Computing becomes economical and accessible to organization size and kind is essential. Quantum Computing is approaching quickly, and will bring about significant changes for which organizations must begin planning now.

LTI
Let's Solve

References

01 Rethinking cybersecurity for a quantum world - Curious (science.org.au)

02 Quantum Computing. Quantum Realm, many of us would agree… | by Vignesh R | Medium

03 Quantum Computing: Top Players 2021 - YouTube

04 The Map of Quantum Computing | Quantum Computers Explained - YouTube

05 VCs make record bets on quantum computing | PitchBook

06 The Path to Building Quantum Advantage | BCG

07 10 Companies Providing Full-Stack Quantum Solutions (thequantuminsider.com)

08 IonQ, Inc. (IONQ) Company Profile & Facts - Yahoo Finance

09 How to get started in quantum computing (nature.com)

10 Amazon Braket Features - Amazon Web Services

11 D-Wave Systems | The Practical Quantum Computing Company (dwavesys.com)

12 Our quantum computing journey | Google Quantum AI

13 Quantum computing software and programming tools (ibm.com)

14 Quantum Development Kit - Quantum Programming | Microsoft Azure

15 Cirq |Google Quantum AI

16 Rigetti Computing - Wikipedia

17 Pasqal - Programmable Atomic Arrays - PASQAL

18 How to program (quera.com)

19 India's first Quantum Computer Simulator (QSim) toolkit was launched by MeitY (indiaai.gov.in)

20 Infosys to Develop Quantum Computing Capabilities on AWS (yahoo.com)

21 QCaaS (thequantuminsider.com)

22 QC Companies of 2022: Guide Based on 4 Ecosystem Maps (aimultiple.com)

23 Quantum Computing: The Risk to existing Encryption Methods by Zach Kirsch (December 15, 2015)

24 http://www.cs.tufts.edu/comp/116/archive/fall2015/zkirsch.pdf

25 Quantum Computing put blockchain security at risk by Aleskey F, Evgenie K and Alexander L (19 November 2018): https://www.nature.com/articles/d41586-018-07449-z

26 The Potential Impact of Quantum Computers on Society by Ronald de Wolf (December 14, 2017: https://arxiv.org/abs/ 1712.05380

27 Oxford's Creating a responsible Quantum Future (March 2021): https://ora.ox.ac.uk/objects/uuid:8e175e19-f879-4827-9cbd-c4849cb6bd60/download_file?safe_filename=Ten_Holter_et_al_2021_creating_a_responsible.pdf&type_of_work=Report

28 A Game Plan for Quantum Computing by Alexandre M, Ivan O, Mark P and Daniel V (February 2020): https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/A%20game%20plan%20for%20quantum%20computing/A-game-plan-for-quantum-computing-v3.pdf

29 The world's data explained: how much we're producing and where it's all stored (theconversation.com)

30 Quantum Computing and The Future of Big Data | ISG (isg-one.com)

31 Quantum Computer Search Algorithms: Can We Outperform the Classical Search Algorithms? | SpringerLink

32 P, NP, NP-Complete and NP-Hard Problems in Computer Science | Baeldung on Computer Science

33 Quantum Computer Search Algorithms: Can We Outperform the Classical Search Algorithms? | SpringerLink

34 Quantum Algorithm (devopedia.org)

35 Linear Algebra (qiskit.org)

36 Quantum Simulation - an overview | ScienceDirect Topics

37 Quantum algorithms: an overview | npj Quantum Information (nature.com)

38 In-Depth Guide to Quantum Artificial Intelligence in 2022 (aimultiple.com)

39 Experimental study on the quantum search algorithm over structured datasets using IBMQ experience - ScienceDirect

40 https://nasscom.in/knowledge-center/publications/quantum-revolution-india-betting-big-quantum-supremacy

41 https://www.gartner.com/smarterwithgartner/the-cios-guide-to-quantum-computing

42 https://news.mit.edu/2016/quantum-computer-end-encryption-schemes-0303

43 The Impact of Quantum Computing on Cryptography and Data – Quantum Strategy Institute

44 https://www.drishtiias.com/daily-updates/daily-news-analysis/quantum-key-distribution

45 https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution?ab=at_art_art_1x

46 Quantum Computing Explained - Clover Infotech

47 https://nasscom.in/knowledge-center/publications/quantum-revolution-india-betting-big-quantum-supremacy

48 https://www.ibm.com/downloads/cas/J25G35OK

49 Nasscom and Avasant Consulting – The Quantum Revolution in India (Feb 2022)
50 Quantum Computing for Artificial Intelligence Based Mobile Network Optimization, Furqan Ahmed, Petri Mähnen (June 2021)
51 Quantum Computing for Finance: State-of-the-Art and Future Prospects (IEEE Paper) Nov 2020
52 Quantum Computing Is Coming. What Can It Do? (hbr.org)
53 Quantum computing use cases--what you need to know | McKinsey
54 Top 20 Quantum Computing Use Cases in 2022 (aimultiple.com)
55 Lloyd's: impacts of quantum computing on insurance – Finadium
56 Industry quantum computing applications – EPJ Quantum Technology (SpringerOpen Journal) 2021
57 The Impact of Quantum Computing on Software Development (oracle.com)
India inches towards quantum supremacy, ropes in Finland (analyticsindiamag.com)
58 China May Have Just Taken the Lead in the Quantum Computing Race - Defense One
59 The Future of Quantum Computing - Interconnections - The Equinix Blog
60 Where does the EU stand in the quantum computing race with China and US? (techhq.com)
61 Quantum Computing: What It Is, Why We Want It, and How We're Trying to Get It - Frontiers of
62 Engineering - NCBI Bookshelf (nih.gov)
63 The current state of quantum computing: Between hype and revolution | McKinsey & Company
Quantum computing in drug development | McKinsey
64 How Quantum Computers Could Cut Millions Of Miles From Supply Chains And Transform Logistics (forbes.com)

Appendix

List of Figures

List of Tables

Authors

Sandeep Deb
CTO, LTI

Sachin Jain
Senior Director, LTI

Bharat Trivedi
Principal – Enterprise Architecture

Chitrang Negi
Research Analyst - LTI crystal & Deep POV

Parag Mhaiske
Trend Analyst - LTI crystal & Deep POV

Sandeep Maheshuni
Specialist - Data Engineering

Vinit Pednekar
Specialist - Package Implementation

Akshans Rautela
Engineer - Cloud Services and Software

Rajasekaran Paramasivam
Senior Specialist - DATA

Anjali Sharma
Senior Specialist - DATA

Vishal Prajapati
Senior Specialist - DATA

Sagar Chauhan
Senior Quality Engineer

Anisa Chowdhury
Engineer - Cloud & Infra Services

Hakimuddin Bawangaonwala
Research Analyst - LTI crystal & Deep POV

Academia

Prof. Anil Prabhakar

Dept. of Electrical Engineering, IIT-Madras

Dr. Chandrashekar Radhakrishnan

Principal Project Scientist at IIT Madras


LTI
Let's Solve