TAKSHASHILA INSTITUTION

A Background to India's Position in the Advanced Computing Age

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Executive Summary

Computational power is a key determinant in advanced computing mechanisms such as high performance, quantum, and cloud computing. Nation-states (and private companies as well) are engaged in a high-stakes race to increase indigenous computing capacity for a number of strategic reasons. This discussion document offers an overview of the advanced computing landscape, including the various types and applications of computational models and devices, and assesses the role and options for India to harness this pivotal technological resource. The document delves into geo-strategic developments related to advanced computing and provides an overview of the current computational capabilities of India, including the supercomputer programme, and the domestic quantum computing landscape in the country. The main takeaways from the document are:

1. High Performance and Quantum computing solutions remain the main market players in the Advanced Computing age.
2. The global High Performance and Quantum Computing landscape are restricted to a group of technologically advanced, financially sound states.
3. India needs to assess the pros and cons of different quantum computing technologies to start and develop its domestic quantum computing programme.
4. The computing landscape in India remains at its infancy with few supercomputers, developed as part of the national mission, and no state financed quantum computing programme (reliant only on public private partnerships till now).

I. Introduction

'Computing power' is the speed at which an information processing system is able to perform a computational task. Overall computing power largely depends on the microprocessors used to construct the computing system, namely the Central Processing Unit (CPU) and, in recent times, the Graphical Processing Unit (GPU).[1] Memory and storage (such as Random Access Memory (RAM)) also play a major role in computing these days. With the concept of parallel processing and multi-core CPUs and GPUs, the processing power of devices has drastically improved to handle lengthy and complex computational processes in a short amount of time.

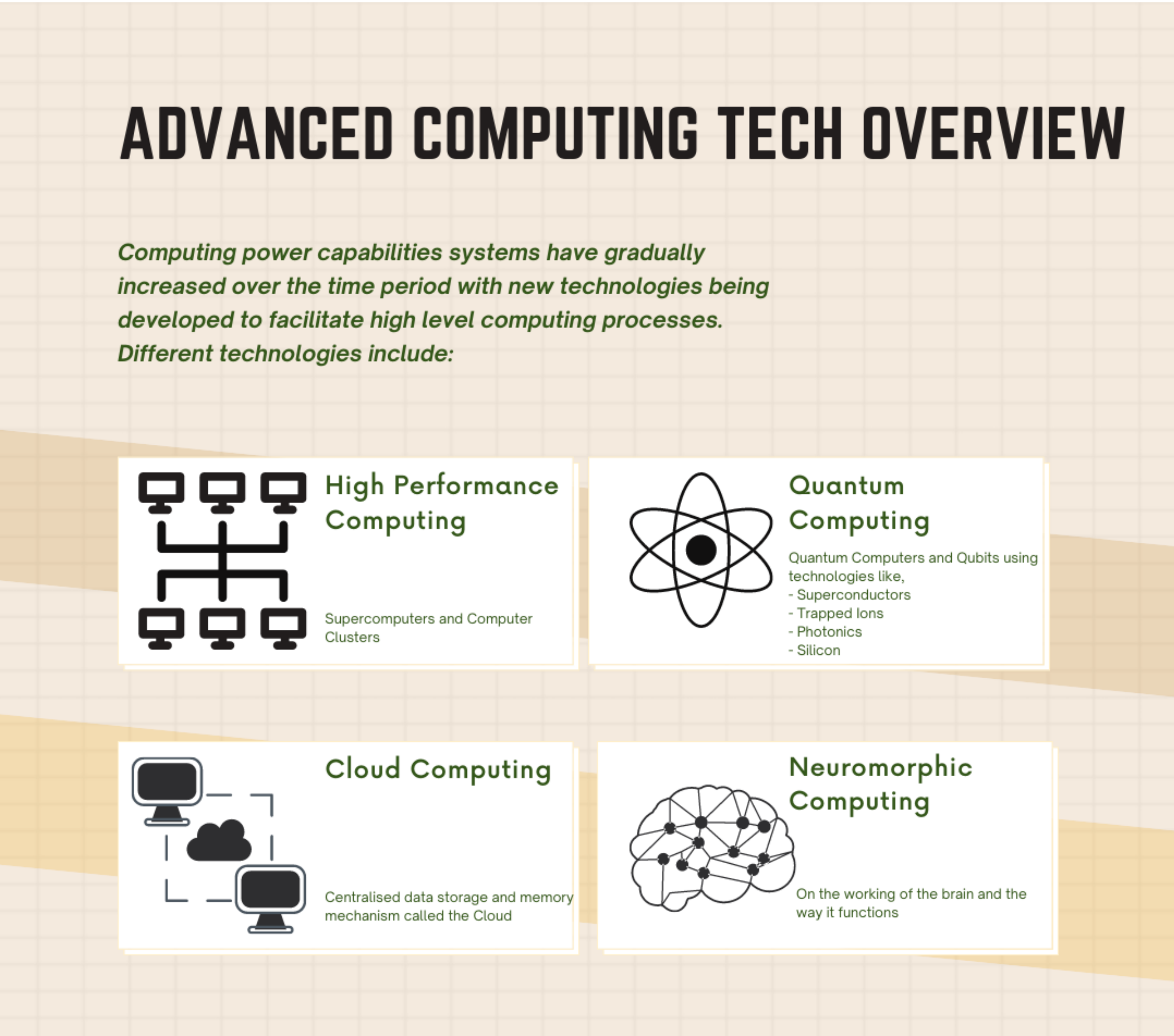

Figure 1: Overview of Different Advanced Computing Technologies

With mass digitisation becoming ubiquitous, people and nation-states rely on the high-speed processing power of computers to conduct almost every aspect of their daily lives. From scientific research and engineering, to logistics management and manufacturing, and from business processes and product development to military hardware, high-performance computing power is an essential tool for the advancement of any modern society.[2]

Though the global computing race has intensified in the past few years, there are some intrinsic bottlenecks for states and private companies to meet their ambitious advanced computing goals. The requirement for cutting edge hardware required has made the role of chip designers central to the computing race and consequently, the global shortage in the supply of semiconductor chipsets has adversely affected the computing programmes of many nation-states.

There is also the issue of high energy and water consumption by these processors and systems which are needed to power and cool down such high-performance computers.[3] While the computing power increases steadily/exponentially with advanced computing mechanisms, the additional costs incurred to keeping these devices running remains a major drawback for those entities looking to increase their capacity in the field.

The development of devices with high computing power such as supercomputers and quantum computers also are severely affected by certain export controls and restrictions put in place for crucial hardware components.[4] Advanced computing mechanisms have attained a protected strategic status resulting in increased techno-nationalist tendencies. Ring-fencing of computing ecosystems and supply chains has resulted in regionalised and localised trade between diplomatic allies. For instance, a multilateral export control agreement such as the Wassenaar Trade Agreement has increased the number of export controls and restrictions related to quantum and semiconductor technologies that are critical in building advanced computing systems.[5]

On the industry side, chip design and manufacturing companies like Intel, NVIDIA, and AMD have continued in their bid to design the fastest ever processors.[6] With the increased role of the private sector, the global computing landscape has become a heavily contested field with multiple state and non-state actors.

The applications of high speed and performance computing are varied as they are ubiquitous. Ranging from small to large scale systems, computational models have become intrinsic to fields from financial services to biomedical science and from smart cities to public health. Meteorology, energy networks and manufacturing industries now require advanced computing due to the scale and complexity at which they function. Not surprisingly, high-performing computing devices are increasingly growing in demand. The global high-performance computing market is expected to grow from a total market cap of $37 billion in the year 2020 to $49.4 billion by the end of 2025.[7] This is a compounded annual growth rate of 5.5% which showcases the increase in demand for these devices.

Specifically, due to the diverse nature of scientific and defence applications that need increased computational power, governments around the world are investing large amounts of money in the field. Simply put, robust and safe computational data models are now integral to smooth functioning of critical sectors like the military and finance that rely on data safeguards.

As computing power and computational devices become increasingly economically and strategically relevant in the Information Age, states are dedicating both scientific and financial resources to the domain.[8] India, while not figuring in the race for supremacy in computing, does have a dedicated programme for developing critical components to be used in such devices. In order to stay relevant, India's actions must focus on leveraging its indigenous resources, coupled with private sector investments, to produce top-class R&D and build machines of globally competitive computing capabilities.

II. High-Performance Computing (HPC)

Dawn of a New Era

The first-ever supercomputer was built in the year 1964 by Control Data Corporation. This was the genesis of the modern-day efforts of high-performance computing. It was followed by the first-ever government-academia funded partnership in 1985 with the National Science Foundation of the US government establishing five research centres for building advanced computing systems.[9] Soon, the concept of advanced computing transcended academia due to the increased demand and requirements for computational models in different sectors.

Advances in high-performance computing (HPC) are required in modern digital technologies to process large amounts of data and perform complex calculations at high speeds.[10] HPC generally refers to the practice of aggregating available computing power in a way that delivers much higher performance than one could get out of a normal or 'classical' computer in order to solve large problems in science, engineering, or business analysis.

To put this in context, an average laptop or desktop computer with top-of-the-line hardware specifications (such as a 3GHz processor) can perform around 3 billion (10^9) calculations per second. However, an HPC device is capable of performing quadrillions (10^{15}) calculations per second depending on the type of hardware and software used.[11]

How Does HPC Work?

The entire HPC architecture hinges on connecting multiple servers (which can vary from a couple of hundreds to thousands) forming an interconnected network or cluster.[12] While each individual server acts like a node in the network, all servers interact with each other in parallel to boost the existing processing speed.

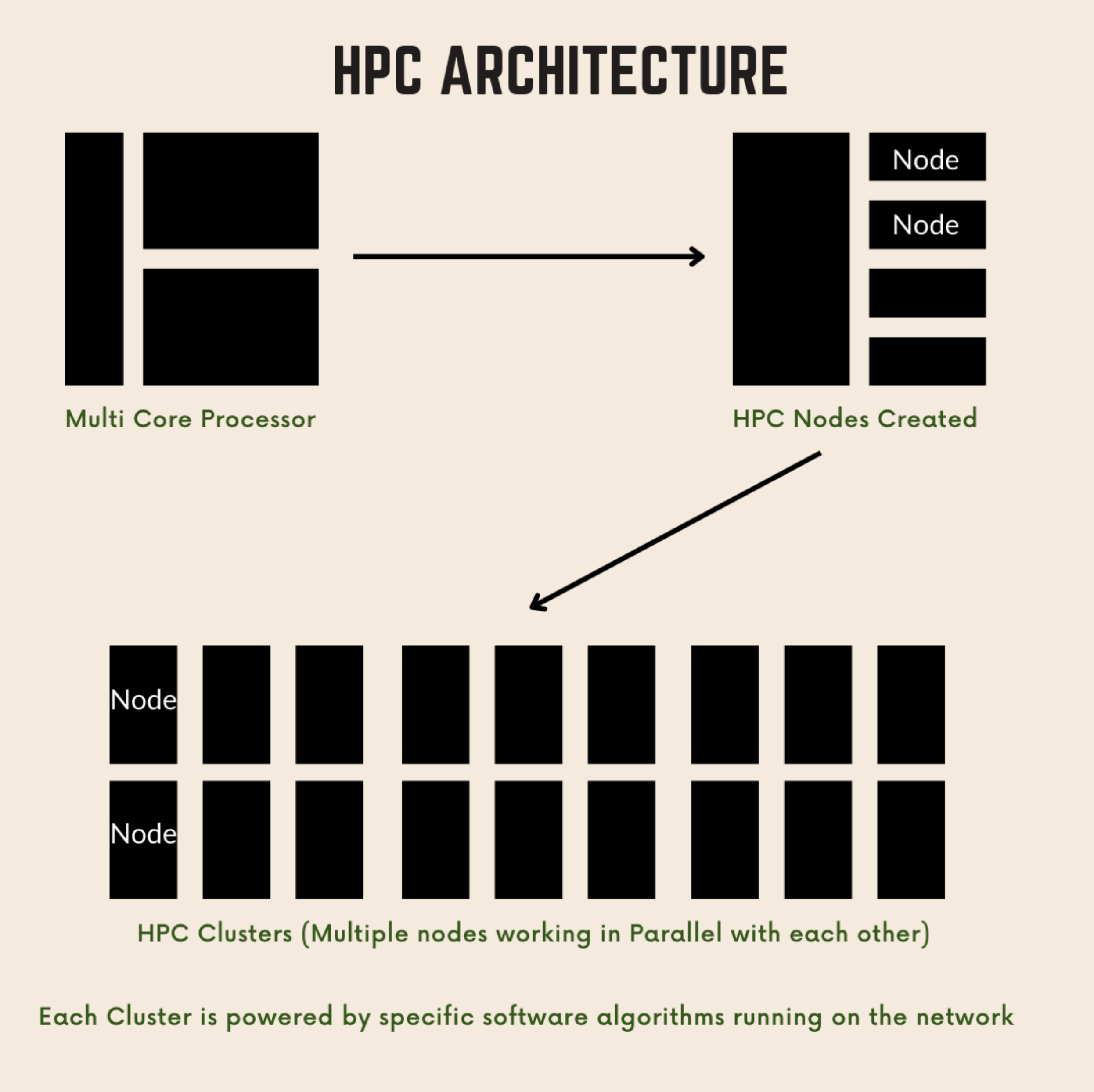

Figure 2: Understanding the HPC Architecture

At the same time, certain software algorithms run at the network level to support the applications of HPC. There is also the presence of a storage component in the system which is connected to the network devices (servers) to capture and store the output of the parallel running applications.[13]

Comparing the architecture of traditional computing systems based on the Von Neumann architecture, the HPC architecture is different in its own way. Traditional systems have a processor (connected to an external memory) controlling all computational processes. However, HPC systems have multiple processes running simultaneously across the network due to the break-up of a single processor into multiple cores and parallel threads (together called a compute cluster) that work in tandem. There is also the aspect of edge-based memory management wherein the compute cluster has the processor as well as memory within it. Therefore, the time taken to fetch data from external memory is greatly reduced in these systems.

The key requirement for the efficient running of the HPC system remains that the network, storage, and computing software components all act in sync with each other. The computing operation starts when servers process the data from the storage components while feeding the processed data instantaneously to networking components. Nearly simultaneously, the software algorithms run the HPC applications while sending back the output to the servers.

This entire process can take place in one of two ways: parallel or tightly coupled.[14] Parallel processing has multiple smaller computational processes running simultaneously and independently without any communication with other processes. Applications include molecular modelling and risk simulations. Tightly coupled, on the other hand, is when smaller processes continuously communicate with each other to complete the required workload. Applications for this form of processing include weather forecasting and traffic management simulations.

(Super) Fast, (Relatively) Cheap, and (Extremely) Versatile: Explaining the HPC Boom

With the evolution and deployment of technologies like Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT), there is a growing demand for handling large amounts of data in extremely quick turnaround times.[15] HPC helps to overcome these computational complexities and latency barriers faced by conventional processors through its decentralised architecture and the capability to perform network edge computing.

The specific benefits offered by HPC solutions can be categorised three-fold:[16]

1. **Speed** - This remains the topmost priority for any HPC device or solution. With the ability of lightning-quick or parallel processing, an HPC device ensures massive amounts of calculations in a very short duration of time. This is mainly

achieved due to the advanced hardware developed specifically for these technologies such as multi-core CPUs, GPUs, and low-latency networking technology like edge computing.

2. **Cost** - Though the development of these large-scale HPC devices like supercomputers needs greater initial investment, the returns offered once set up are incredibly cost-effective. The quicker turnaround time can help save money as well as complete more tasks both effectively and efficiently. These HPC solutions can also be scaled up or down depending on the needs, further lowering the costs of running the systems.
3. **Simulations** - HPC systems are capable of running advanced simulations which reduce the need for physical testing of systems. This means a minimisation of repetitive tests required to ensure proper functioning of computer systems. The capability of HPC solutions to create state-of-the-art simulations to track the performance of computer systems is a step-change in the computing field brought about by eliminating time-consuming testing processes.

Applications of HPC systems are widespread and range from analytics to simulation modelling. Analytics include operations management and supply chain optimisation while simulations include autonomous driving and financial management, among other things.

Globally, the growth of the HPC market looks to increase in the coming decade with a projected market cap of $66.5 billion by the year 2028. The compounded annual growth rate (CAGR) for the market for the 5-year period from 2017 to 2022 was pegged at 9.8%. This increase in the HPC market share has been enhanced by the low/sinking costs and greater affordability of new hardware.[17] HPC Cloud Power, which looks at solutions to improve computing power in cloud data centres and communications infrastructure, is set to become the predominant contributor in the HPC market with a CAGR of 17% predicted till the year 2024 for this specific technology. The economic prospects, coupled with the strategic benefits that HPC offers, have made the field both commercially lucrative yet intensely contested at the same time.

III. Quantum Computing

While HPC is utilised for high-speed computation (via parallel processing units or a supercomputer), quantum computing (QC) leverages the behaviour of nano-scale particles described in quantum mechanical theory to perform its computational processes. Due to the superposition principle (described in the section below), quantum computers, while not necessarily quicker than classical or HPC computers, are adept at solving many optimisation and scheduling problems that deal with enormous data sets, making them invaluable in areas such as cybersecurity, cryptography, and blockchain technology, amongst many other emerging application domains.[18]

Quantum computing has emerged as the most promising of all quantum-enabled technologies currently and has taken precedence in both the government and private sectors. We are now in a situation where technology giants like Microsoft, Google, and IBM are spending billions of dollars on the development of next-generation quantum computers, while at the same time, national governments of advanced industrial powers like the US, UK, and China are formulating and funding their own National Quantum Missions and Programmes, all with the stated ambition of developing indigenously manufactured advanced quantum computers.[19]

The last decade has seen exciting breakthroughs (like quantum supremacy/adequacy being met) in the field of QC, in large measure due to the massive investments being poured by the public and private sector. These innovations are a major boost to the computing domain and those actors looking to build their computational capabilities. It also signals the potential of the sector and the possibility of new applications arising from the field. A wide array of sectors have benefitted from quantum computing to create simulation modelling (aeronautics and aviation), large-scale data analytics (space and cosmology programmes), forecasting (weather and climate), and building encryption systems (military and defence).[20]

Even though it's considered emerging technology, there are multiple technologies that are still under research for the creation and implementation of qubits (the building blocks of a quantum computer) which raise the strategic importance and the economic criticality of the field of quantum computing in the near future.

The Principle Behind QC

The field involves the use of quantum bits or 'qubits' which can handle any value between 0 and 1 at any point of time moving away from digital bits of 0s and 1s. Qubits/quantum bits are the basic units of information stored in a quantum computer capable of adopting multiple states (hence any value between 0 and 1) based on the principle of superposition. This allows qubits to store and compute data on a much larger scale compared to a normal computer. Coupled with the principle of entanglement which links independent particles together, the computing power increases to a great extent. These systems are able to perform calculations based on the probability of an object's state before it is measured - instead of just 1s or 0s - which means they have the potential to process more data compared to a classical computer.

The use of qubits helps in optimisation, search, and solving certain problems at an extremely quick pace due to their quantum superposition state.[21] The computing power of these systems dwarfs that of the power of supercomputers when addressing specific types of computing tasks, and helps decode issues that might take classical computers hundreds, if not thousands, of years to decipher.

While the principles behind the working of a quantum computer remain the same, advances in the field have improved the ways to optimise device performance. There are several ways to operationalise qubits and each technology used to build the component parts of a quantum computer has its own advantages and disadvantages. Private companies and government labs also differ in their approach to building quantum computers with each entity looking to achieve 'quantum supremacy' (the ability of a quantum computing system to solve a problem that no classical computing system can solve in any feasible amount of time) through their own preferred qubit harnessing technology.

Types of Quantum Computing Technology

There are many ways to design and develop a computing environment capable of harnessing quantum technology. With a varied quantum value chain (the components needed to build quantum devices) and the ability to use different technologies to build quantum computers, the idea of which path to take is a difficult one. Different private companies are specialising in their own technology to come up with faster and better quantum computers. Governments, depending on the external dependencies, focus on certain technologies to build national quantum computers capable of serving the public sector.

Each quantum computing technology has to be viewed from a national power perspective with each having its own advantages and disadvantages. Some might be easier to implement due to internal comparative advantages while some may have external restrictions that can hamper the project. It is necessary to understand the different technologies used to build these quantum computers so that India can try and specialise in particular technologies to kickstart its own quantum computing programme.

TYPES OF QUANTUM COMPUTING TECHNOLOGIES

TYPES	ADVANTAGES	DISADVANTAGES
Superconducting Qubits **Companies Involved**: Google AI Quantum, IBM, Rigetti, D-Wave	• Already established advanced semiconductor fabs • Plenty of existing research	• Need for superconducting materials • Cryogenic cooling systems • Competition from private industry
Trapped Ions **Companies Involved**: IONQ, Honeywell	• Scale, accuracy, and computational capability • Low error rate	• Decoherence due to negative interaction with environment • Relatively new and evolving area
Photonic Computing **Companies Involved**: PsiQuantum, Xanadu	• No need for cryogenic systems • Can be interwoven with fiber-based communications	• Excessive bulkiness • Extremely volatile due to susceptibility to noise
Silicon Spin **Companies Involved**: Intel, Silicon Quantum Computing	• Low levels of noise • Based on existing microchip technology	• Problem of integrating both microelectronics and silicon qubits into single-chip
Neutral Atoms **Companies Involved**: QuEra, Cold Atom, Atom Computing	• Less energy required to run optimisation and simulation algorithms • Stability of system for a longer duration of time	• Other cooling systems required to keep it running • Need for error-correcting codes and fault-tolerant algorithms

Figure 3: Comparison of Quantum Computing Technologies

Superconducting Qubits

The most popular technology to build quantum computers employs the concept of superconducting qubits. These qubits are built on the principle of using superconducting materials/devices to create quantum particles that exhibit the properties of superposition (the ability of particles to exist across multiple states at the same time) and entanglement (two or more particles linked such that they cannot be described independently) and also have the capability to pass through energy barriers that normal particles cannot cross through.[22]

This technology gained headlines when it was realised that superconducting materials and objects on a micro or nanoscale developed using semiconductor fabrication techniques could also behave like quantum particles.[23] Advanced semiconductor fabrication techniques can help in using superconducting materials like quantum dots.

The quantum state of these particles is then controlled and manipulated using electromagnetic pulses which create superconducting circuits along with the key components of qubits, which ultimately form the building blocks of a quantum computer.[24]

With superconductors being the most advanced of all technologies to build quantum computers, major investments need to be made in this specific technology by most of the major players in the global market. This is with respect to the use of cryogenics, which is needed for cooling and maintaining extremely low temperatures to ensure superconductivity. There are also export restrictions on cryogenic systems that prevent easy access to them.[25]

This is already a crowded field with major private companies indulging in research and development. Funding and allocation of revenue are primarily directed towards the private sector in this technology. Google's quantum computer, Sycamore, which was unveiled last year, was the fastest computer ever developed at the time of release, utilised the superconducting qubit technology to build their quantum computer.[26] The company specifically focuses on the superconducting technology for its AI Quantum programme. Similarly, another technology giant, IBM, which was officially the first company to have a dedicated quantum computer programme, also uses superconducting devices to build their quantum computers.

Trapped Ion Systems

A growing alternative to superconducting qubits, trapped ion systems, is gaining traction in recent times due to its flexible nature and the ability to use the technology to build large-scale quantum computers. In this technology, charged particles, also called ions, are suspended and 'trapped' in free space using electromagnetic fields. Lasers are used to maintain the position of these particles and control entanglement between them. The qubits, which form the basic structural components of a quantum computer, are created within the electronic state of all the ions.[27] With this, quantum information can be processed and transferred through the collective motion of these ions in the shared trap.

While still in the development phase, trapped ion systems have a large advantage in terms of scale and accuracy when compared to other technologies used to build quantum computers. The possibility of using ion arrays to create a large number of qubits for better computational capacity is an advantage. It also aids the possibility of creating large entangled states using ion chains which can help in the scalability of the system itself.[28] This could be helpful if India has a dedicated national quantum computer to handle the enormous scale of the data processed.

Trapped ion systems have reported the lowest quantum error rate till now, making it a promising technology one for the development of future quantum computers.[29]

Very few private entities specialise in this technology, with companies like IonQ and Honeywell having managed to build computing systems exploiting trapped-ion technology.

Since it remains a relatively new field, not many governments have invested in this type of technology to build their quantum computers. There is also this external dependency that causes decoherence in the system if the created qubits interact negatively with the environment or surroundings. Typically financed by start-ups and the fledgling private sector, the trapped ion technology is still an evolving area that needs significant expertise which India currently does not possess.

Photonic Computing

Photonic computers are quickly gaining mainstream traction. They are based on a technology that works with the concept of photons carrying qubits instead of charged particles like ions and electrons. These devices use infrared lasers along with resonators to generate the quantum states of multiple photons. The light stream, now consisting of quantum entangled photons, is sent through beam splitters that perform the computational processes.[30] Finally, these photons are passed from the chip through detectors (mostly made of superconducting materials) to extract the answers for the processes.

Xanadu, a Canadian technology company, now specialises in the development of cloud-accessible photonic quantum computers. China's University of Science and Technology (USTC) has also come out with the world's fastest photonic quantum computer in 2021.[31]

Entities undertaking research in this specific type of quantum technology have claimed an advantage over the others due to the fact that they do not require expensive cryogenic freezers (for cooling the devices to very low temperatures) and can work at room temperatures.[32] One of the other reasons many firms prefer this type of technology is the fact that it can be interwoven with existing fiber-based telecommunication infrastructure, and can therefore help build a large-scale quantum network and internet.[33]

Hurdles do exist for this type of technology in the form of the excessive bulkiness of the systems, as well as the configurability of the circuit itself. It is extremely volatile due to the dependency on photons that are susceptible to any interference or noise.

Silicon Spin

Another way of creating qubits involves the use of silicon within semiconductor devices themselves. This technology involves the controlling of spin characteristics of charged particles (like electrons) and using the spin (½) degree of freedom of individual particles as qubits. This was first proposed by Prof. Bruce Kane at the University of New South Wales (UNSW) in 1998, when he claimed that individual atoms in Silicon could be used to store qubits.[34]

A major advantage of using silicon to create qubits is the relatively low levels of 'noise' environment that the element offers. With quantum states being highly fragile and susceptible to any kind of disturbance, silicon is a material that ensures that the spins could retain their quantum states for a longer period of time.[35] This means that any quantum information being stored is far more secure than it would otherwise be in other forms of quantum storage.

Another critical aspect of using silicon is the application of tried and tested microchip technology used in 'classical' computers as this technology has been around for a longer period of time, and is also favoured due to the ready availability of semiconductor hardware.[36] The technology is lucrative for those countries that have an abundant supply of raw silicon deposits and facilities for its production into microchips.

But there are also inherent roadblocks to this technology. For example, scientists are still trying to figure out a mechanism to integrate both microelectronics and silicon-spin-based qubits into a single chipset.

The concept of using traditional semiconductor devices like transistors as qubit carrying devices, and using them interchangeably as quantum computing devices, is definitely an exciting but difficult prospect in this regard. Semiconductor giants like Intel and Hitachi have been involved in the field and are looking to come out with advanced quantum computers made of silicon.

Neutral Atoms

Broadly similar to ion-trap systems, this type of quantum computing technology primarily utilises atoms that have an equal number of protons and electrons. Each atom is configured in a two or three-dimensional method. Having done that, individual qubits are encoded into each energy level of the atom itself. The qubits retain their three-dimensional nature similar to the host atom, as well as interact with each other in space. This also provides a multitude of ways to develop topologies to encode qubits depending on the kind of computational processes involved.[36]

The concept of using neutral atoms means less energy is required as it avoids the need for cryogenics (freezing atmospheres). The fact that the qubits can still retain and maintain the three-dimensional structure helps in different processes such as simulation and optimisation.[37]

The easier conditions for development and more advantages in terms of returns on offer have caught the attention of many start-ups and other companies looking to get into the quantum computing business. QuEra is a quantum start-up founded by MIT students who have developed a 256-qubit quantum computer using this type of technology.[38]

While this technology promises to be reliable in the long run, there still remains the issue of cooling systems in this type of environment. While cryogenic style cooling is not necessarily needed, there are still extensive cooling systems requirements needed to operate and maintain this quantum computing system.

There is also the issue of error-correcting codes and fault-tolerant computations which still require some work to reduce the error rate that exists when certain algorithms are run on a neutral atom quantum computer.

Other than the above five technologies, there are still upcoming technologies looking to entrench themselves in the quantum computing era. Technologies like Atomic Vapours (for the creation of photonic polarisation qubits), as well as Nitrogen-Vacancy Centres (also known as NV Diamonds where the individual NV centres in the diamonds are used for the creation of qubits), are also gaining traction in the domain with new entrants looking to break into the field. With more investments from governments, as well as the private sector looking to play a pivotal role in the future, the quantum computing field and associated technologies will remain highly competitive in the years to come.

IV. Other Forms of Advanced Computing

While High Performance and quantum computing remain the leaders in advanced computing mechanisms, recent years have seen the growth of alternative forms of computing processes and technologies. These offer alternatives to nations looking for the opportunity to scale and build up their indigenous computational power as well as diversify their processing capabilities.

Cloud Computing

Cloud-based remote-access computing has become one of the most important technological developments in the past decade. The ability to deliver computing services over the internet has replaced bulky computing hardware with software models. "The Cloud", which is the name given to the parts of the internet and global networks handling computational resources, is made up of all traditional components required to build an advanced computing system: servers, storage, software, and networking all remain interwoven in the cloud and work in harmony with each other.[39] This means an HPC or another advanced computing solution is mimicked using specific software algorithms themselves. This innovation can create faster-performing resources and economies of scale for their users.

The non-requirement of big hardware components along with the need for big storage spaces for housing these devices is a major advantage for those opting for cloud computing. The allocation of resources is also better managed with clients. Users are only required to pay and use the cloud services they absolutely require. This effectively lowers operating costs and helps build a more efficient computing environment. It is also easier to scale up the computing capability depending on the current needs.

Edge computing is an interesting application of this technology. This is possible with the use of the cloud where the processing happens at the network's edge (a device with its own cloud storage) rather than a centralised system.[40] This considerably improves the speed at which computing processes take place. It is imperative in certain applications such as autonomous vehicles that need fast decision making and computational abilities.

The advancements in cloud computing have also brought the concept of digital and cybersecurity to the forefront.[41] The protection of data and information from potential threats have become a primary requirement for those using computing devices. Cloud computing offers a relatively more secure and reliable infrastructure with security protocols and algorithms in place by design, rather than added later on. The other major advantage of the cloud remains the ability to back up data and information, hence eliminating the prospect of losing all valuable data in case of damage to the systems or a cyber-attack. The storage mechanism in the cloud is built in a way that computational data can be mirrored at multiple redundant sites on the cloud provider's network.

Technology companies like Microsoft, Amazon and Oracle have become pioneers in the cloud computing domain. Microsoft's Azure and Amazon's Amazon Web Services (AWS) offer cloud services on a large scale to multiple businesses and governments alike. Governments have been turning to cloud services to process and store critical data that might be of national security concern.[42] It is a matter of time before the cloud takes over as the primary source of computational processes due to its accessibility, enhanced security and low-cost usage options.

Neuromorphic Computing

A relatively new entrant into the field of computing, the concept of neuromorphic computing builds on the empirical working of the brain. It analyses how a computational model can be designed based on the neurological functioning of this central processing human organ.[43]

Moving away from the traditional Von Neumann architecture (shared memory for the program and data) model of processors, the neuromorphic model keeps the fundamentals of high-end processors while decreasing the wait time of data travelling between the storage/memory and processing unit.[44] The brain's capability to parallelly process information also helps in the faster turnaround time. With high-end error correction and fault-tolerant systems still under development for advanced computing devices, there is now a rationale for using the human brain as an alternative model for computer processor units.

Neuromorphic computing models work similarly to how the brain's neural networks function. The intrinsic arrangement between the neurons, brain parts, and receptors is duplicated through specific hardware components (memristors) and software algorithms.[45] In humans, neural networks are spiked or triggered through electromagnetic pulses, causing the receptors to send signals through the neurons to the brain. The brain processes these signals and sends back the action to be taken back to the sensory organs. The exact same decision-making technique is used replacing the brain with an electronic processor, and memristors which are used as storage devices. Memristors also have the ability to store a range of values rather than just digital bits of 1s and 0s.

This also means that a neuromorphic model mimics the external environment and conditions in which a brain functions. A number of advantages are seen in this model. A normal human brain requires around 20% of the body's total energy as its source of power. When compared to the scale of a normal supercomputer, the amount of power that a neuromorphic model requires is a lot lower than a supercomputer. There is also the aspect of advanced computing solutions like supercomputers and quantum computers requiring cooling systems when compared to a human brain / neuromorphic computing model which functions best at room temperatures.[46] An argument can also be made that the versatility and adaptability of the human brain offer the neuromorphic model more options in the computational data processing. This could therefore be the technology that helps humankind move beyond traditional computing models and techniques.[47]

Despite being a new entrant into the computing field, neuromorphic devices have already seen high levels of interest from technology giants. Intel, for example, has its own neuromorphic chip called Loihi and also has its own neuromorphic system called TrueNorth.[48] It recently announced a partnership with the United States Air Force Research Lab for piloting a neuromorphic supercomputer mainly for military applications.[49] The adaptability factor can help in simulating real-time battlefield scenarios and developing concrete military strategies. There is also the fact that neuromorphic chipsets are being used to develop smaller military devices like unmanned aerial vehicles (e.g., drones) and other lethal autonomous weapon systems to increase the warfare capability of states and their military.[50]

However, the biggest caveat for the field of neuromorphic computing is the fact that firms are still a long way from achieving the goal of modelling the entire brain or even major systems within it. Currently, the leaps made by technology firms in this area of computing have developed and modelled specific sensory applications but have not achieved much beyond that. For example, current neuromorphic sensors only attempt to mimic the sensing and visual processing characteristics of living organisms. This is to reduce the computational load for visual perception especially in the post processing stage. Neuromorphic computing still has a long way to go in terms of replicating the brain's complete working capabilities itself.

V. The Global HPC Landscape

A Tri-Polar World Emerges

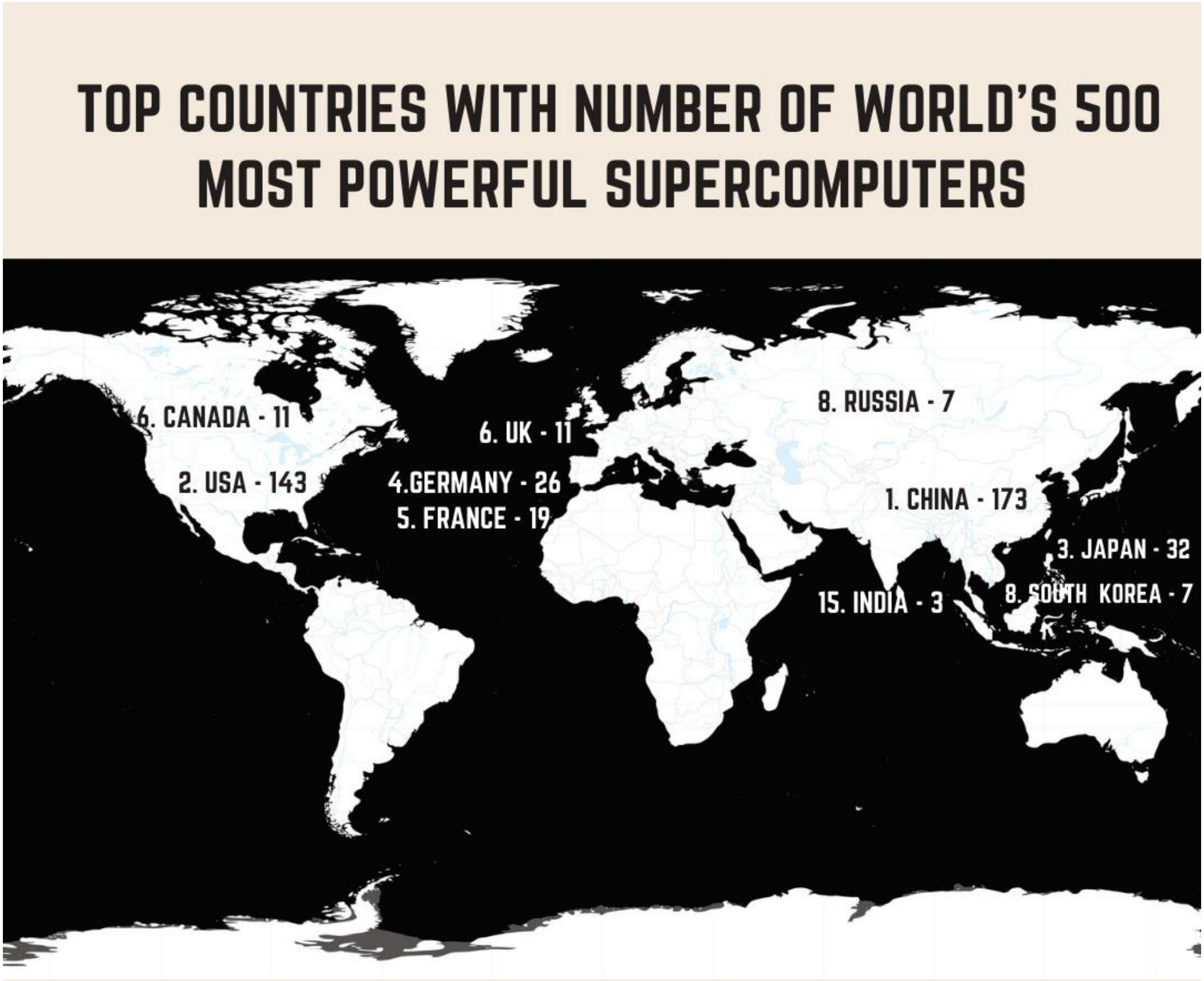

Figure 4: Distribution of World's Top 500 Powerful Supercomputers in the World

The last decade has seen a considerable increase in the number of HPC's technical applications and areas of strategic influence. This has resulted in advanced technological powers like the United States, Europe, and China formulating their own strategies for the development of large-scale HPC devices and solutions. The development of HPC devices like supercomputers and exascale computers (a high-performance computing system that is capable of at least one exaflop per second i.e., more than 10 floating-point operations per second) are heavily state-driven due to their high setup costs and national security implications and so governments around the world are actively involved in allocating human resources and finances towards building their own HPC ecosystems.

While the United States has long been the leader in high-performance computing, it took decisive steps since 2015 to cement its HPC capabilities with a wary eye on China's burgeoning rise in this sphere. To wit, the US National Strategic Computing Initiative was launched by the government in July 2015, specifically for the development of exascale systems.[51] Currently, the US houses around 122 supercomputers on its territory with many designated for building computational data models for various sectors.

In 2012, the National Nuclear Security Administration of the US government started utilising a network of supercomputers to simulate nuclear weapons capability. Gradually, non-military applications have increased.[52] The National Oceanic and Atmospheric Administration (NOAA) currently uses a supercomputer (Weather and Climate Operational Supercomputing System) for weather forecasting, predictions, and tracking oceanic weather activity.[53] National security domains such as cryptography and private sectors like petroleum and automotive industries rely on supercomputers

China, despite being a rising technological power, was a late entrant to the HPC field, but now leads the world with over 180 supercomputers across its territory.[54] The state-driven approach, coupled with extensive industry-academia collaboration, has helped China leapfrog others like the US and Europe in building HPC capabilities. The country's National Supercomputing Centres (NSCCs) program has identified 8 national centres (with 2 more to be identified) for housing supercomputers concentrated in the mid-eastern and mid-southern regions of China.[55]

The Supercomputing Centre of the China Academy of Sciences (SCCAS) is located in Beijing and is the operations centre for China National Grid (CNGrid). The centre in the city of Tianjin houses the world's fastest supercomputer. Guangzhou houses the fourth fastest supercomputer in the world. The cities of Guangzhou and Shenzhen house the fourth-fastest and third-fastest supercomputers in the world, respectively. Other cities to house supercomputing centres include Shanghai and Chengdu. In late 2021, there were reports that China officially possesses two exascale systems (OceanLight and TaihuLight), with a third one currently under development.[56] The 14th 5-year plan of the Chinese Communist Party (CCP) also states that the priority of the government would be to build 10 exascale systems in the country by the end of 2025.[57]

Europe's computing ambitions were initially driven by the French government's stated objective to be autonomous while ensuring that they have access to new and critical technologies. This objective to build an indigenous French computing champion materialised in the form of the company Atos.[58] Atos has a dedicated Big Data and Cybersecurity division meant for the production of high-performance computers and servers. It clocked a yearly revenue of around 11 billion euros in 2020, with the computing division contributing to around 20% of the company's overall revenue.[59] In terms of Europe as a whole, the field of HPC has been allocated abundant financial resources to build the region's capability, most notably via the EuroHPC project, which was kickstarted in 2019 with an initial budget of 1 billion euros.[60] A joint undertaking by seven major European Union (EU) states (Germany, France, Spain, Italy, Greece, Portugal, Netherlands, and Sweden) as part of the project (and now includes Switzerland as well), established the Exascale and European Processor Initiative (EPI) for extreme-scale computing.[61]

This Exascale initiative, part of EuroHPC, called for the development of 2 exascale machines by 2023 (in France and Germany) along with the development of 3 pre-exascale machines and 5 petascale machines (petascale: a high-performance computing system that is capable of at least one Petaflop per second i.e., can perform more than 10^{15} floating-point operations per second) during the same timeline. The first petascale machine in Europe was inaugurated in March 2021 in Slovenia. Out of the 3 pre-exascale machines commissioned under the project, two are already under construction - one is LUMI in Finland (a joint effort between Hewlett Packard Enterprise (HPE) and Advanced Micro Devices (AMD)) and the other is Leonardo in Italy (a joint effort between Atos and NVIDIA). [62]

The European Processor Initiative was announced in 2018 along with the main roadmap to deliver a high-performance, low-power processor that can be used in HPC systems. Under this initiative, the company SIPearl (a Franco-German chip design company responsible for designing processors under EPI) is developing the processor Rhea (based on an ARM design), specifically for exascale machines.[63] There are multiple other processors being developed under this initiative for technologies like electric vehicles, edge computing, and large-scale data centres.

VI. The Global Quantum Computing Landscape

More Players, but Same Leaders as HPC

While major technology giants have thrown their hats into the ring with their own in-house quantum computer programmes, states and their governments around the world are not far behind. The bulk of the funding of government policies related to quantum technologies is set aside for the development of state-of-the-art quantum computers.

The United States government has recognised quantum technology as a critical area due to its economic prosperity and national security concerns. The government launched the National Quantum Initiative in the year 2018 with a total budget overlay of $1.2 billion over the following 5 years. A National Quantum Coordination Office was established within the White House to oversee the implementation of the programme.[64] A majority of the funds were dedicated to building quantum research facilities along with an additional $237 million allocated as part of the 2021 Budget. Quantum computing and the development of quantum computers got the lion's share of the initial funding from the government.

An added advantage for the United States is the presence of American private sector companies which are actively involved in the development of quantum computers. Tech giants like Google, IBM, and Microsoft now offer online programming and cloud services to build and access quantum computing applications. Quantum computing has clearly become an area of concern for the US with regard to China's rise in the domain as well as potential military applications of the technology so it is not surprising that techno-nationalist tendencies have been showcased by the American government in this regard. For instance, the Export Control Reform Act (ECRA) was extended to quantum technology products in 2018. This included critical quantum refrigerators and cryogenics along with software and AI for quantum cryptography.[65] This was done in order to make cross-border collaboration with Chinese nationals and academic institutions more difficult.

As noted, the response of the US directly relates to the rise of China in the domain. As the global leader in patents related to quantum communication and cryptography, China has advanced by leaps and bounds in the quantum computing domain over the last decade. Once behind the West in developing quantum computers, China now houses two of the world's fastest quantum computers on its soil. The pace at which China has adopted quantum computing technology is truly exceptional, with the country claiming 'quantum advantage' in both the superconducting qubit and photonic system technologies.[66] Immense state support has been provided by the Chinese government to both academic institutions (University of Science and Technology China (USTC), Tshinghua and Peking Universities) and private companies (Origin Quantum, Qasky, and Huawei Cloud) for the development of quantum computers in the country. The advances made by China in the domain of quantum computing have resulted in increased global protectionism in the field.

Europe and its constituent countries have also invested and started their own quantum technology programmes. From bigger technologically advanced countries like France and Germany to up-and-coming technological powers (Switzerland, Sweden), many states in the European Union (EU) have embraced quantum technology especially, quantum computing. As a whole, the EU has created a 'Quantum Flagship' initiative to develop applications related to quantum technology. The United Kingdom (UK) in 2021, announced the setting up of a National Quantum Computing Centre by 2023. The announcement also mentioned an MoU with the company Rigetti to build the UK's first commercial quantum computer.[67] Germany recently commissioned the construction of two new quantum computers with the first one being unveiled at Fraunhofer Institute in June 2021.[68] France has become a major spender in developing quantum technology with research institutes like Paris-Saclay and private companies like Atos working to develop faster and better quantum computers with alternative technologies.

Tactics to secure comparative advantage have been used by the West to block access to critical components needed for building quantum systems. For example, restrictions have been placed on refrigeration technologies needed for supporting cryogenically cooled quantum computers. Bilateral agreements between the US and UK, Canada, and Australia have proposed to decouple quantum research efforts and the value chain from Chinese access.[69] This ring-fencing of quantum computing technology research has broadened the already existing fissures in this arena.

VII. India in the Advanced Computing Age

India has been gradually ramping up its computational capability over the years. The Government of India has started taking active steps in upscaling the level of advanced computing technologies across the country. Schemes (such as the National Superconducting Mission) have been announced and investments (roughly in the 5000-10000 crore range) have been allocated to increase the scale and number of advanced computing devices or solutions. While these have been welcome moves, there still exists plenty of room for improvement to ensure effective implementation of these programmes.

The Indian HPC Landscape

The announcement of the National Supercomputing Mission (NSM), announced in 2015 by the government of India, was the first step taken by the state in the field of High-Performance Computing technologies.[70] The NSM is a jointly funded programme between the Department of Science and Technology (DST) and the Ministry of Electronics and Information Technology (MeitY). The implementation partners for the mission are the Centre for Development of Advanced Computing (C-DAC) in Pune as well as the Indian Institute of Science (IISc) in Bengaluru. A total outlay of Rs 4500 crore has been allocated for the mission over a period of 7 years (2016-2023). Around 60% of the total budget is to be financed by DST while the remaining will be by MeitY.

With a long-term vision of building a robust High-Performance Computing (HPC) environment in the country, the main objectives of the National Supercomputing Mission include:[71]

1. Creation of state-of-the-art HPC facilities and infrastructure to enhance the national capability to enable cutting-edge research in various computational domains.
2. Development of HPC Applications for major science and engineering domains.
3. Promote Research and Development in HPC leading to next-generation exascale computing readiness.

4. Human Resource and research development to handle and spearhead HPC activities in the country.

The government announced the creation of three Mission phases (all starting concurrently) under the NSM for the efficient implementation of the programme.[72] These include:

- Phase-I: Assembled in India
- Phase-II: Manufactured in India
- Phase-III: Designed and manufactured in India.

Depending upon the process of setting up the supercomputers, each phase has a dedicated number of supercomputers to be installed across the country. A total of 15 supercomputers are targeted to be deployed under NSM Phase-I (till the end of 2018) and Phase-II (completed by September 2021), at specific identified end-user host institutes.[73] Over 50 academic and research institutes have been selected to house these supercomputers and form an interconnected National Supercomputing Grid as its backbone. This form of interconnected structure of supercomputers would help a lot of academic researchers, scientists, and engineers leverage the advantages of supercomputers. All Phase-II supercomputing systems are set to be manufactured in India, by local Electronic Manufacturing Services (EMS) dealers and are equipped with an indigenous software stack. The Phase-III supercomputing systems are set to be designed by C-DAC and manufactured in India by local EMS dealers.

The lack of official roadmaps is an obstacle in tracking the real time progress of these phases In response to a question by a Lok Sabha member dated 19 March 2021, the Minister for Science and Technology, Dr Harsh Vardhan, elucidated the progress of the national Mission and the milestones that have been achieved in the HPC domain by India.[74] As per the response, under the NSM, 6 supercomputers have been installed and established to date at these locations in the country, which are as follows:

1. IIT-BHU, Varanasi
2. IISER, Pune
3. IIT Kharagpur
4. JNCASR, Bangalore
5. IIT Kanpur
6. National Facility for AI, C-DAC

Apart from the above supercomputers under the NSM, the Minister stated that various other institutes house supercomputers, with another 9 supercomputers being established at other academic and research institutes across the country.

The Minister also mentioned that the government departments in charge of the national mission, DST and MeitY, have collectively provided a total of Rs 1060 crore towards developing supercomputing facilities for research and other allied areas like application development and training, etc, in the HPC domain. As of the date the response was given, funds equivalent to Rs 531 crores had been utilised, and commitments of Rs 428 crore had been made on various activities including purchase orders.

This shows that there have been some credible advancements made in the HPC sector due to the intervention and support provided by the government. However, the developments have been restricted to government-funded projects only. The domestic private sector in the country has not yet dipped its toes into the domain due to costs, infrastructure, and regulatory reasons. High costs of building cooling systems for advanced computing devices, high import tariffs on electronic components needed to build supercomputers, the volatility of consistent power and water supply to keep the systems running are just some of the roadblocks that private companies face.

However, there has to be a mechanism to build a public-private partnership model in the HPC domain. Indian startups and firms involved in building computational infrastructure must be provided with financial support so that they can develop indigenous HPC solutions. Along with financially encouraging the Indian domestic sector of computational firms, the government has the ability to strike collaboration agreements with international technology companies involved in the HPC market offering incentives to shift their HPC operations to the country. There is also the aspect of the Indian government facilitating collaboration opportunities between the still developing domestic industry and the international firms who are leaders in HPC.

The Quantum Computing Landscape

While India has a dedicated supercomputer programme in the form of NSM, there has been no dedicated government policy towards the field of quantum computing. Instead, the 2020 Budget speech saw the announcement of the National Mission on Quantum Technologies and Applications (NM-QTA). This, though not dedicated towards the development of an indigenous quantum computer, supported building an overall quantum technology ecosystem across the country.

The NM-QTA officially kickstarted the government's increased focus on quantum technology in the country.[75] While the government has not formulated a plan specifically for quantum computing, the domestic private sector has gotten involved in the development of quantum computing hardware, software, and algorithms.

The year 2021 was a landmark year for quantum technology initiatives in India. Early in the year, the Ministry of Electronics and Information Technology (MeitY) announced a tie-up with the technology giant, Amazon, specifically the Amazon Web Services (AWS) branch of the company, to set up the country's first-ever quantum computing lab.[76] Called the Quantum Computing Applications Laboratory, the lab will house state-of-the-art quantum computing hardware, simulators, and programming tools for scientists and researchers to work with. The government states that 'the lab is meant to provide access to a quantum computing development environment for the developer, scientific and academic communities.

In late 2021, the research firm Ingoress decided to tie up with the State Government of Gujarat to build the country's first-ever quantum technology park. Currently labelled the Greater Karnavati Quantum Computing Technology Park (GKQCTP), it looks to be the torchbearer of Indian quantum technology development, including design, engineering, testing, and manufacturing.[77] The intent behind the construction of the tech park is to also attract potential collaborations with corporates and startups involved in quantum computing research and development.

Alongside government funding, a concomitant increase in the participation of the private sector can also be witnessed in the Indian context. A global pioneer in quantum computing, IBM India has decided to start the IBM Quantum Educator programme in the country.[78] This is a collaboration between the company and top scientific-educational institutions such as IITs for upskilling in the field of quantum computing. The programme involves IBM providing students with quantum computer prototypes, Qiskit (open-source software by IBM), and other resources to improve research and education in the quantum computing field.[79]

Apart from major technological companies engaging in building the quantum ecosystem, there are a number of thriving start-ups in India working on developing quantum computing applications. Companies like Qnu Labs and Automatski have shown credible growth in the quantum computing field. Security products using quantum computing and the development of different types of quantum computers (such as adiabatic and annealing computers) have taken off with these firms.

Despite a lack of initial investment, the quantum computing landscape in India is gradually growing with the increase in participation of private sector players (both tech giants and startups) and deals made by private entities with the government. While NM-QTA was announced in 2020, there has been very little movement in the allocation of funds and kickstarting projects. The government needs to acknowledge the importance of quantum computing, both economically and strategically (military applications), and ensure that investments and financial support are provided for the development of quantum computing applications in the country.

IX. Conclusion

Advanced computing methods have the capability to alter national power and raise the bar for technological superiority. States (with the necessary competency) around the world have started specific programmes to build their computational prowess. Supercomputers, quantum computers, and other technologies like edge and cloud computing are taking over the domain. Devices capable of solving complex problems with minimal time and effort have been built in recent years and this has the potential to disrupt traditional models and systems in use. National security concerns in terms of military systems getting compromised, and encrypted systems being easily hacked by these advanced computing devices have raised the question of how far these technologies can increase a state's overall power.

India, being a responsible and growing technology power, has the capability to build on its existing computational power. The government has acknowledged the economic and geopolitical benefits that advanced computing devices might offer. The NSM has focused on HPC while the newly announced NM-QTA hopes to develop an indigenous quantum computer. It also has to understand the benefits of other advanced computing mechanisms and facilitate government-assisted programmes for them too. Investments for building these advanced computing devices are indeed high, but returns offered are economically and strategically just as high. Hence, it is imperative that the government take the first steps towards building a robust ecosystem across diverse advanced computing models now, so as to safeguard India in the future.

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