Quantum computers as hardware accelerators for parallel processing: A perspective

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Abstract

Quantum computers are inherently parallel processing devices by nature of their design. In this era of parallel processing and artificial intelligence, quantum computers need to be widely adopted. Towards this goal, quantum computers need to be reoriented as a hardware accelerator for parallel processing. By adopting hybrid physical systems that contains atomic and optical components, and with further miniaturization, quantum computers are marching towards the goal of becoming part of mainstream computing.

Keywords: Parallel processing, quantum computing, 3D rendering, quantum parallelism

1 Introduction

Application with a technology can deviate from the initial design of the inventor. This is true for various inventions in history [1]. The first satellite launcher from Soviet Union was in fact a modified intercontinental ballistic missile. So is the case of microwave oven, turned out while testing a radar equipment. The internet which is used world over was designed as a communication network connecting military bases in the United States. These are some of the technologies which are spin offs from their initial intended application. In this era of artificial intelligence, similar promising approaches are required for making quantum computing a viable technological platform. Rather than approaching quantum computing as a sophisticated device for specific applications, it is always beneficial to incorporate this niche technology towards mainstream computing. This is similar to the role of Graphics Processing Units (GPU) and other
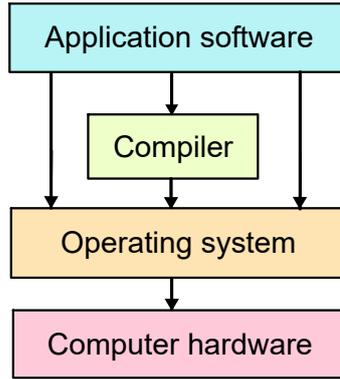
Fig. 1: Layers involved in parallel computing.

hardware accelerators in general purpose computing [2]. In this article, the use of quantum computer as a hardware accelerator for parallel processing is explored. Parallel processing is a realm ruled by advanced GPUs for decades. Quantum computers with its processing capability can transform the technological landscape of parallel processing. By orienting and developing hardware and software parts of quantum computing towards parallel processing, it is easier to integrate it into general purpose computing platforms.

2 Parallel processing

It is a common practice among integrated circuit designers to increase the number of processing cores in a microprocessor to increase the computational performance. The increase in number of cores adds to parallel processing capability of the microprocessor [3]. Typical microprocessors sold in market have anywhere between two to twenty four processing cores in it. A GPU which is sought after for higher levels of parallel computing has thousands of cores in it [4]. Number of processing cores and clock frequency are determinantal in performance of a microprocessor. In parallel processing, processing cores execute the program in parallel. This is in contrast with serial processing wherein the program is executed serially by the processing core. Programs written for parallel processing need to utilize the processing cores effectively for enhancing the efficiency and performance. Many programming techniques are developed for effective utilization of processing cores which results in faster execution of programs, enabling performance. Layers involved in parallel processing is illustrated in Fig. 1. This includes the underlying hardware which consists of processing cores, the intermediate layer consisting of operating system and compiler, and the topmost layer which is the application software. The application software interacts with the compiler and operating system to get the parallel processing strategy executed by the hardware. In addition to processing cores, integrated GPU or dedicated GPU works as a hardware accelerator in executing the parallel processing tasks. An overview of GPU parallel processing for 3D rendering is given below.
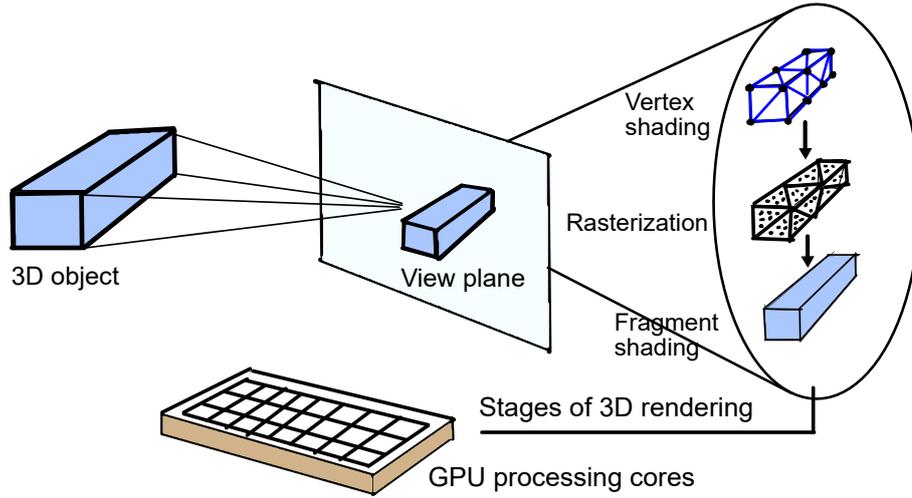
Fig. 2: 3D rendering stages in a graphics pipeline.

2.1 GPU based parallel processing

Rendering is the process by which 3D objects are projected into a 2D view plane for visualization [5]. GPUs are the mainstay of a rendering pipeline, a series of steps involved in the rendering process. In a 3D game environment, the moving objects need to be continuously rendered for visualization. Rendering pipeline is also known as graphics pipeline (see Fig. 2). A typical graphics pipeline consists of a series of key stages, viz. vertex shading, rasterization and fragment shading. 3D objects in the scene are modeled as triangles with vertices. Each of these vertices and triangles need to be projected into the view plane with the proper color and lighting to get a photo-realistic visualization of the 3D scene. The process of projecting each of the vertices and triangles into the view plane is known as vertex shading. This involves a series of transformation applied on the vertices using matrix math. Each of these projected vertices and triangles are represented as pixels on the display device. This stage of representing triangles as pixels is known as rasterization. Each of these rasterized triangles are given color as from the 3D scene. These pixelized triangles are known as fragments. The lighting provided in the 3D scene gives it a photorealistic visualization. The fragments are correspondingly shaded based on the 3D scene. This stage of giving proper shading for fragments is known as fragment shading. For faster rendering of the 3D scene, graphics pipeline require parallel calculations to be executed on a group of vertices and triangle elements. These calculations which are done parallelly are executed by thousands of cores in the GPU. For higher frame rates, faster rendering is achieved by parallel processing of GPU cores.

3 Quantum computing

As transistor based digital logic gates reach their ultimate limit in miniaturization, new technologies are sought to take forward the computing performance to the next

level. The most promising technologies in this race are quantum computing and optical computing [6]. Optical computing makes use of light for computing, and is gradually transforming into a reliable platform with the introduction of logic gates based on photonic technologies [7]. Quantum computing on the other hand has many competing platforms which vary in their computational performance and reliability. Some of the platforms which are commonly employed for quantum computing include NMR, ion trap, superconducting circuits, and so on [8]. When compared to current generation of semiconductor microprocessors, quantum computers are at their nascent stage of evolution. Albeit, for complex problems, there is an upper hand for quantum computers over their classical counterparts in computational performance. This is referred to as quantum supremacy [9]. Quantum computing technologies are coming of age, and many of the systems are at the verge of commercialization. An energy efficient, compact, and scalable platform is the ultimate aim of research in this area. Some of the hardware platforms and theoretical framework for implementation of quantum computing is illustrated below.

3.1 Theoretical framework

When size of the structure (integrated circuit component) is reduced to the size of atom, quantum effects creeps in, and it would be difficult to explain the observed physical phenomenon based on classical laws of physics [10]. This was conveyed by Feynman by mentioning that nature is not classical. Feynman also proposed a computing scheme based on laws of quantum mechanics, today known as quantum computing (QC). Taking into account the quantum nature of these quantum computing platforms, novel algorithms were proposed for these systems [11]. These algorithms which can run only on a quantum computing platform can execute codes at a fraction of time than their classical counterparts. This was one of the motivation factors for venturing into the realm of quantum computing in the first place. Quantum computers can be used as universal computers, to execute either classical or quantum algorithms. When a classical algorithm is executed, the performance of quantum computer will be at par with a classical computer. But, when a quantum algorithm is executed, it outperforms a classical computer. Quantum algorithms can be executed only on hardware (platform) designed for quantum computing.

For any physical system to be suitable for quantum computing, it has to satisfy certain requirements. Firstly, the ability to represent information as qubits (quantum bits) in a quantum register. Secondly, the ability to perform logical operations on quantum register. Thirdly, the ability to read out the result from a quantum register. Current generation of quantum computers are prone to errors because of external disturbances (surroundings), and are known as Noisy Intermediate Scale Quantum (NISQ) computing [12]. A robust quantum computing platform which can withstand interference from surrounding medium is the focus of research in this area. A general-purpose quantum computer remains a distant possibility as the technology is not yet matured, be it be hardware or software. As an interim measure, special-purpose quantum computers are more appealing and realistic. This article is exploring the feasibility of quantum computer for parallel processing.
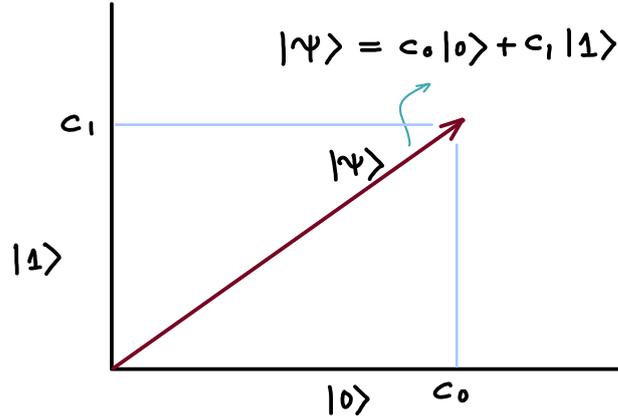
Fig. 3: Representation of qubit $| \psi \rangle$ as superposition (linear combination) of two orthogonal basis states, $| 0 \rangle$ and $| 1 \rangle$.

In conventional digital computer, information is stored as a series of bits, either 0 or 1. Electronically, logical states, 1 and 0, are represented by high voltage and low voltage respectively. In a quantum computer, the logical state is represented by a quantum bit (qubit). The platform which is commonly employed for quantum computing is a two-level system. A qubit represents and takes the value which is a superposition (linear combination) of these two logical states. Mathematically, this is represented by

$$| \psi \rangle = c_0 | 0 \rangle + c_1 | 1 \rangle \tag{1}$$

where $| 0 \rangle$, $| 1 \rangle$, are the two logical states and $| \psi \rangle$ represents the state of the qubit. Here, c_0 and c_1 represents the probability amplitudes along $| 0 \rangle$ and $| 1 \rangle$. This is better illustrated in Fig. 3. Equation 1 is the case of a single qubit. A quantum computer can have N number of qubits. If all these qubits are entangled, the state of the system can be represented by a superposition (linear combination) of 2^N mutually orthogonal basis states. Logical operations done on this superposition state is equivalent to doing 2^N operations in parallel. The computing power of a quantum computer stems from this parallelism that is inherent to a quantum computing system. Specifically written quantum algorithms exploit this parallelism and put it to good use, and thereby enable quantum computers to outperform supercomputers.

Quantum register consists of an array of qubits which stores information in the form of logical states, viz. $| 0 \rangle$ and $| 1 \rangle$, for a two-level system. Just like a register in a classical computer, quantum register also need to be initialized to zero before starting computation. Usually, initialization is done to the quantum mechanical ground state. Logical operations are done on a quantum register by quantum gates. A quantum algorithm makes use of a series of quantum gates to implement a logical operation on the quantum register. Once all the instructions on the algorithm are implemented, the resulting state of the quantum register denotes the output of the quantum computer.
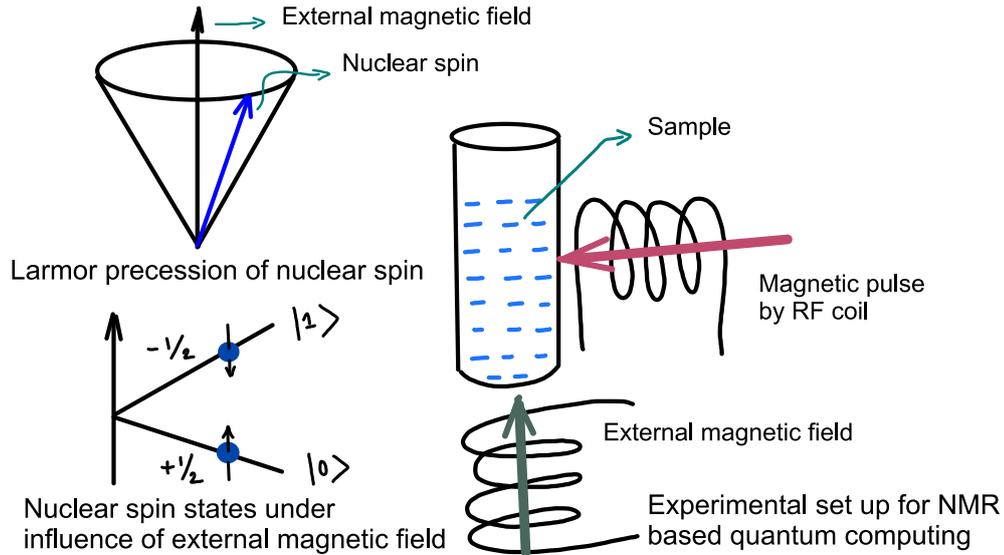
Fig. 4: NMR based quantum computing.

4 Quantum hardware

Some of the physical systems deployed for quantum computing is illustrated below. Among these, NMR system is first physical system to exhibit quantum computing. Ion traps and superconducting circuits are benchmark physical systems used for achieving quantum computing. Each of these physical systems have different approaches and control systems in place for realizing and operating on qubits they create.

4.1 NMR system

Nuclear magnetic resonance (NMR) is a technique used to visualize nuclear spin states of a given sample. When an external magentic field is applied to a given sample, nuclear spin degeneracy is broken, and the splitting of nuclear spin states occurs, known as nuclear Zeeman splitting [13]. Spectrum of nuclear Zeeman sublevels is called NMR spectrum. For a spin 1/2 system, two nuclear Zeeman sublevels (+1/2 and -1/2) are formed on application of an external magnetic field, as shown in Fig. 4. When an external magnetic field in applied, the nuclear magnetic moment tries to align parallel to this field in order to minimize magnetic energy. Moreover, the nuclear magnetic moment precess about the external magnetic field with Larmor frequency. For a spin 1/2 system, this precessional motion which is aligned with the external magnetic field corresponds to the lower nuclear spin state. It is possible to flip the nucleus to higher nuclear spin state by applying an energy equivalent to difference in energy between nuclear spin states. Interestingly, Larmor frequency corresponds to this energy difference. In this way, flipping between nuclear spin states is possible by applying energy equivalent to Larmor frequency. This is a resonant phenomenon
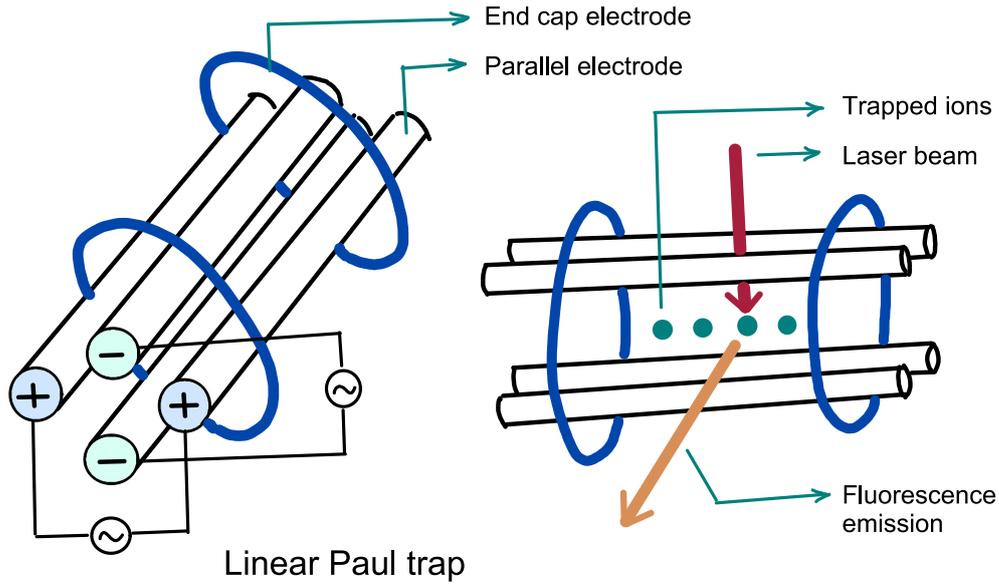
Fig. 5: Ion trap based quantum computing.

wherein the flipping occurs only at Larmor frequency, and hence the name nuclear magnetic resonance.

Magnetic pulses are applied to flip the nuclear spin states. These magnetic pulses are generated from a RF (radio frequency) coil kept perpendicular to the external magnetic field. Incoming magnetic pulse rotates the precession angle by $90°$, and makes the nuclei orient towards the coil. This precession of nuclear magnetic moments against the axis of the coil induces an electric signal in the coil. This is the NMR signal. This signal which is in the time domain is converted into frequency domain using Fourier transform, and the NMR spectrum is obtained. When the magnetic pulse is withdrawn, the NMR signal starts decaying. Gradually, realignment of nuclear magnetic moment occurs towards the initial angle of precession, under the influence of external magnetic field. Succeeding magnetic pulses can again rotate the precession angle and make the nuclear moments orient towards the axis of coil, and the process is repeated. It is possible to make use of NMR as a platform for quantum computing. Here, the spin states of nuclei in the sample act as the qubits. Logical operations are done on the NMR qubits by applying magnetic pulses from the RF coil. The read out of data from the qubits are possible from the collected NMR signal.

4.2 Trapped-ion system

Electrostatic potential does not have a minimum in the free space, and cannot be used for trapping ions [14]. Due to this, ion trapping is usually done by suitably designed time varying quadrupole potentials [15, 16]. Commonly, quadrupole traps such as linear Paul trap is used for trapping ions for quantum computing (see Fig. 5). Linear Paul trap consists of a set of parallel electrodes with AC voltage and end cap
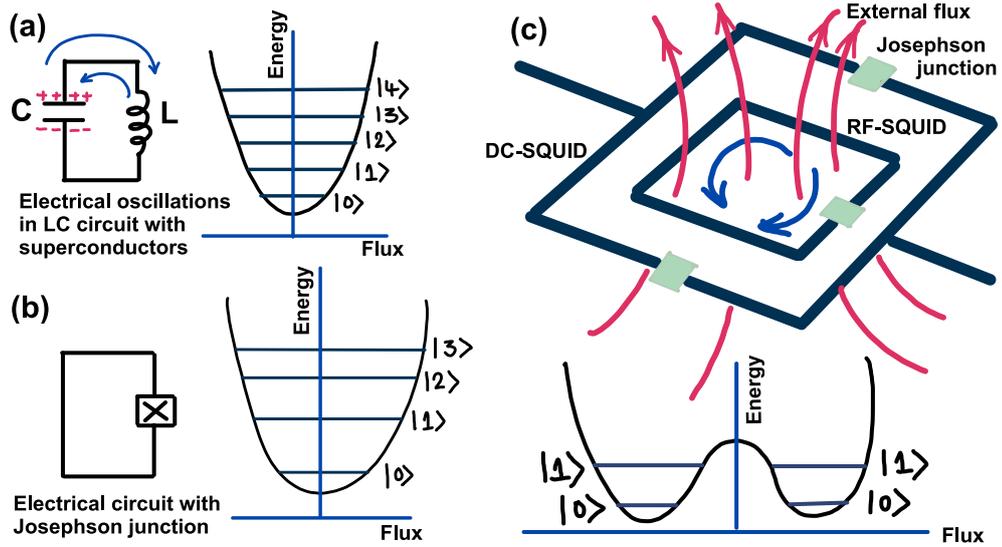
Fig. 6: Superconducting circuits based quantum computing.

electrodes with DC voltage. Ions are produced by knocking our electrons from neutral atoms. Once ions enter the linear Paul trap, because of switching of polarity of AC voltage continuously, ions are confined between the parallel rods, along their length. End cap electrodes prevents the leakage of ions along the longitudinal direction. Since evenly charged ions repel each other, there is good spacing between ions, and a linear chain of ions in formed in the trap.

Qubits are represented by electronic ground state and excited states of ions, for $|0\rangle$ and $|1\rangle$ respectively. For proper working, motion of ions need to be reduced, and this is done by laser cooling. Quantum register is initialization to the ground state by optical pumping. Logical operations are done on qubits by illuminating laser pulse on ions. Read out is possible by tuning the laser for a particular state which in turn emits fluorescence photon which is detected by a photo detector.

4.3 Superconducting circuits

Superconductivity is a phenomenon by which electrical resistance of certain materials falls to zero at very low temperatures near absolute zero. Electrical oscillations in superconducting circuits can form qubits for quantum computing [17, 18]. It is a known fact that electrical oscillations can be generated in a circuit with a pair of inductor and capacitor. There is electrical resistance even for good conductors, whereas electrical resistance is zero for superconductors. Moreover, electrical oscillations in superconducting circuits are quantized i.e. only discrete energy values can be taken by the oscillator. As it is known, superconducting loops can have persistent current even without a voltage source. This is due to the absence of electrical resistance in a superconducting loop. In a quantum harmonic oscillator with inductor and capacitor, energy levels are equally spaced. This type of quantum oscillator with equal energy

level spacing is not suitable for representing qubits as this can give rise to inconsistency in energy required for switching between qubits. In other words, addressing specific qubits become difficult. In order to create an unequal energy level spacing, a Josephson junction is introduced in a superconducting loop [19]. A Josephson junction is formed by sandwiching a thin insulator in a superconducting loop. When thickness of this insulator is small, supercurrent flows across the insulator. This phenomenon is known as tunneling.

Josephson junction is a non-linear circuit element which adds capacitance and non-linear inductance into the superconducting loop. As a result, unequal energy level spacing in introduced in superconducting oscillator. Now, ground state and first excited state of the quantized oscillator can represent $\mid 0\rangle$ and $\mid 1\rangle$ qubits respectively. As a two-qubit system is preferred, other than the lowest two states, all higher lying energy levels are avoided. This is done by giving external biasing in form of current, voltage or magnetic flux. Based on the biasing that is provided externally, there are three different types of qubit circuits possible with Josephson junctions. They are phase qubit, charge qubit and flux qubit. Here, flux qubit is considered in detail. Typical circuit for a flux qubit consists of a RF-SQUID surrounded by a DC-SQUID as shown in Fig. 6. RF-SQUID stands for radio-frequency superconducting quantum interference device which consists of a superconducting loop with a single Josephson junction. DC-SQUID stands for direct current superconducting quantum interference device which consists of a superconducting loop with two Josephson junctions. DC-SQUID provides the flux bias to the RF-SQUID. Because of the flux bias, the quantum oscillator potential well gets modified to a double potential well. Flux qubit is a superposition of clockwise and anticlockwise persistent currents that exist in the RF-SQUID which in turn is represented as degenerated energy states in double potential well. Transition between ground state $\mid 0\rangle$ and first excited state $\mid 1\rangle$ is possible by application of microwave pulses which can be utilized for logical operations. Read out is possible by the same DC-SQUID which is also a sensitive magnetometer. The number of Josephson junctions in RF-SQUID and DC-SQUID varies based on electrical parameters set by the circuit designer.

5 Hybrid systems and quantum parallelism

In addition to physical systems discussed in the previous section, there are many more hardware systems which can realize quantum computing [20]. Among all systems, superconductor circuits based system is the forerunner due to the versatility, scalability and ease of fabrication with semiconductor process technology. The disadvantage is in maintaining ultra-low temperatures required for superconductivity. Another point of contention between superconducting circuits and ion trap is regarding coherence time. Coherence time is the time for which a qubit can maintain its state before losing fidelity (decoherence) by interacting with the environment. When it comes to coherence time, ion trap system is a clear winner. In order to achieve the scalability of superconducting circuits and coherence time of ion traps, hardware designers have considered hybrid systems. Hybrid systems couples an atomic system with an optical system. Usually,
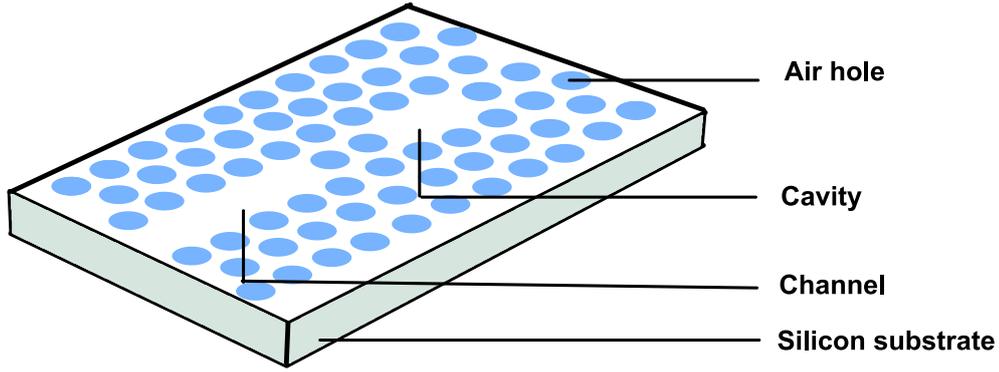
Fig. 7: Photonic crystal based hybrid system for quantum computing.

atomic systems have high coherence time, whereas optical systems have good scalability. In this way, a hybrid system uses the best of both worlds approach for creating high performance quantum systems. One such system is considered here.

The hybrid system considered here consists of optical cavities in photonic crystals slabs. Photonic crystals are periodic dielectric structures which can have optical bandgap in certain frequency ranges [21]. Cavities or channels in these structures can have light confinement or propagation through it with minimal loss [22]. Cavities in photonic crystal slabs can accommodate qubits for quantum computing. Qubits in the cavity can be realized with any of the quantum systems discussed earlier. It can be realized with atomic condensates or even a photon condensate [23]. Coupling between cavities in photonic crystals can be achieved with channels running through these structures. In this way, quantum computing with this type of hybrid systems can achieve coherence time and scalability at the same time. Fig. 7 shows cavities and channels in a photonic crystal slab. Photonic crystal slabs can be easily fabricated by conventional semiconductor process technology which makes it suitable for scaling.

5.1 Quantum parallelism

Quantum parallelism refers to the ability of a quantum computer to parallel process a transformation on n basis states of an input superposition state in a quantum resister [24]. Any input given to the quantum register is a superposition of n basis states. If x is the input superposition state, the transformation y = f(x) will be done at the quantum register for each of the n basis states of x. The output y is also a superposition state of n basis states. In other words, when the input is superposition of n states, quantum computer computes simultaneously on each of these n basis states to get the required output transformation. This is known as quantum parallelism. This is illustrated in Fig. 8. This process is analogous to 3D rendering done by a GPU where the features from the 3D object is transformed for visualization on a 2D view plane. Thus, quantum computer is also capable of doing parallel processing tasks done by a GPU. Quantum computers can run both classical and quantum algorithms. When a scalable quantum computer based on a hybrid system is realized, it will have the capability to handle parallel processing tasks of a GPU as well as run sophisticated
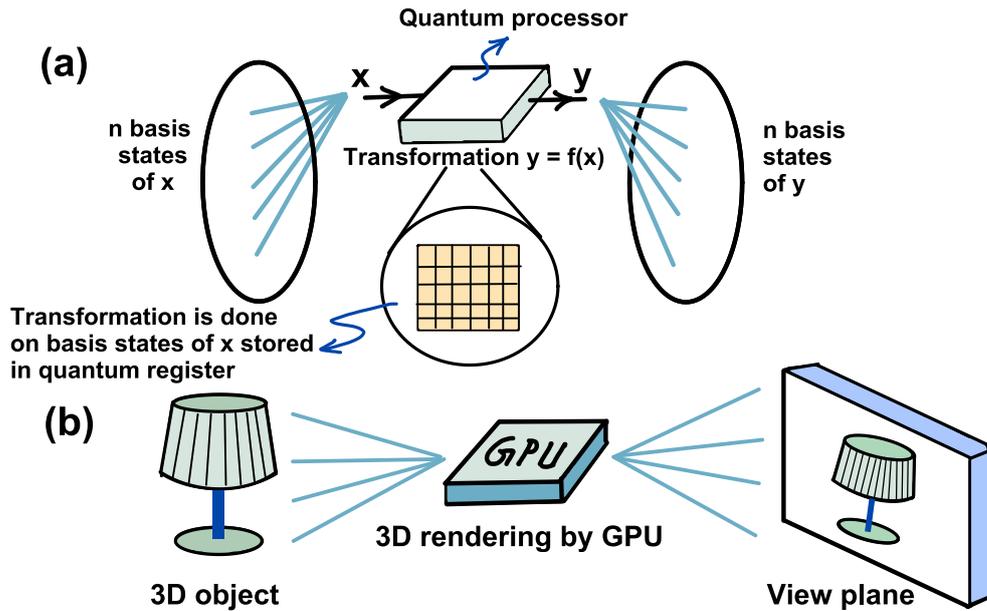
Fig. 8: Comparison of quantum parallelism and 3D rendering by GPU.

quantum algorithms. Quantum computer with this dual capability is analogous to a tow capable truck which can run with or without towing based on the requirement. In this way, quantum computers are set to be integrated into mainstream computing platforms.

6 Conclusion

Parallel processing is an area getting focused in recent years to increase computational performance. Quantum computing due to its inherent parallel nature can be employed for parallel processing along the lines of graphics processing units. Drastic miniaturization need to be adopted before they can be employed as hardware accelerators for parallel processing. In the near future, there will be hybrid quantum computers with optical and atomic components working hand in hand to run classical or quantum algorithms based on software requirements. It is better to orient the software and hardware parts of quantum computers towards such an era by improving competitiveness and productivity.

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