



## Quantum Physics and its Profound Impact on Human Society

**B. N. Dev**

*Centre for Quantum Engineering, Research and Education (CQuERE), TCG Centres for Research and Education in Science and Technology (TCG CREST), Sector V, Salt Lake, Kolkata, India e-mail: [bhupen.dev@tcgcrest.org](mailto:bhupen.dev@tcgcrest.org)*

### ABSTRACT

Quantum physics emerged from the failures of classical physics to explain many physical phenomena. Quantum physics has contributed immensely to science and underpinned modern technologies. The UN-designated International Year of Quantum Science and Technology (2025) recognizes the centenary of the birth of quantum mechanics as a complete theory and its profound contribution to the first quantum revolution, which has given us computers, mobile phones, lasers, GPS and MRI. Also a second quantum revolution is poised to provide unprecedented computing ability through quantum computers, secure communication with quantum cryptography and ultrasensitive quantum sensing devices for various diagnostic tools.

### 1. Introduction

The behaviours of macroscopic objects that we encounter in daily life are well explained by classical physics. However, microscopic particles like electrons or atoms do not obey classical physics. So, classical physics cannot describe their behaviour. The deficiencies of classical physics for microscopic particles were addressed with the development of quantum physics, which involves the study of matter and energy at the fundamental, atomic and sub-atomic levels. For non-specialists, the lessons and principles of quantum mechanics are difficult to understand because they often have no analogies in the experience of daily life and they are not perceptible to the human senses. However, quantum physics has already revolutionized humanity by underpinning modern technology. It has enabled essential innovations like transistors, computers, lasers, atomic clocks and GPS (global positioning system), MRI (magnetic resonance imaging) scanners etc. Future advancements in technological applications of quantum physics promise breakthroughs in quantum computing, secure communications, drug discovery, innovative materials, and sustainable energy.

The dawn of the 20<sup>th</sup> century heralded the advent of quantum physics. Max Planck introduced the idea of energy quanta in 1901 to explain the blackbody radiation spectrum [1], which classical physics was unable to explain. An early success for quantum physics was Niels

Bohr's model of the atom as a small solar system with discrete orbits for electrons. Introduced in 1913, Bohr's model [2] successfully reproduced the absorption and emission spectra of hydrogen, but it had trouble with more complex atoms. Quantum mechanics, a specific fundamental mathematical theory within quantum physics, was introduced in 1925 by Werner Heisenberg [3]. Louis de Broglie theorized that a moving particle had an associated wave, which led to the concept of wave-particle duality in quantum mechanics. In 1926, Erwin Schrödinger derived the wave equation, known as Schrödinger equation, that is central to modern quantum mechanics [4]. It was soon proven that Schrödinger's formulation was equivalent to Heisenberg's matrix mechanics formulation. As physicists were already familiar with wave mechanics, Schrödinger's approach rapidly gained popularity. The year 2025 marked a significant milestone in science, not only because it was the 100th anniversary of the formulation of quantum mechanics but also because the United Nations, recognising the importance of quantum science and the need for wider awareness of its past and future impact, proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ). IYQ was observed throughout the year all over the world via organisation of various programmes in quantum science and technology.

Quantum physics has fundamentally transformed our understanding of nature and our existence. Without quantum physics, our understanding of the microscopic world would be incomplete, and our modern technological society would not exist in its current form.

Quantum physics has also had a lasting impact on the philosophy and our perception of reality by challenging classical notions of determinism and locality. Quantum physical effects do not directly correspond to our daily life experience. It is difficult to comprehend that a particle can take two different paths simultaneously if not observed in the interim, and that the two particles, light-years apart, can behave in the same way as if they have an invisible connection. In essence, quantum mechanics shook the foundations of classical mechanics and its entire view of the world.

## **2. Quantum Technology**

The insights of quantum physics are the foundation of quantum technology. Towards the development of quantum technology utilising the fundamental knowledge from quantum mechanics, a major milestone was the work of Felix Bloch [5], who proved a theorem that allowed the description of the behaviour of electrons in the periodic structure of crystalline solids. This theory offered the basis for the concept of electronic band structures, the understanding of which for semiconductors led to the development of transistor [6]. That seed of quantum technology, a transistor, flowered into today's mobile phones and powerful supercomputers which contain tens of billions of transistors. Understanding of atoms led to the development of lasers, atomic clocks and GPS, where each satellite of the GPS system contains highly precise atomic clocks. Quantum tunnelling phenomenon has been utilised to develop the most powerful microscope, the scanning tunnelling microscope, which enables us to "see" individual atoms [7, 8]. Quantum mechanical model of "particle in a box" explains the energy levels of quantum dots [9]. The "particle in a box" model along with quantum tunnelling have been used to develop quantum cascade lasers [10]. Magnetic resonance imaging (MRI) scanners utilise nuclear magnetic resonance and

superconductivity, both quantum phenomena. All these technologies belong to what is called the first quantum revolution, which began with the invention of transistor in 1947.

### 3. Classical vs Quantum Computers

The present-day personal computers, laptops, and the most powerful computers - supercomputers - are classical computers. They are built with transistors, which are based on underlying quantum physics as explained in Section 2. However, during the first quantum revolution, two important quantum properties of the microscopic objects were not used for the development of quantum technologies. These two properties are called (a) *superposition* and (b) *entanglement*. *Superposition* means that a quantum particle can be at more than one positions, or more than one quantum states, simultaneously. *Entanglement* means that two quantum particles can be connected (entangled), irrespective of their distances, in such a way that if the state of one particle is determined by a measurement, the state of the other particle will be automatically known without any measurement. These concepts are counterintuitive but real. The Physics Nobel Prize of 2022 was given for demonstrating, through different experiments, that entanglement is a reality. During the last three decades these two properties of quantum systems, *superposition* and *entanglement*, have been in use for the development of quantum computers, quantum communication and quantum sensors. These developments heralded the second quantum revolution, which is having a profound impact on current technological development.

In communication, cryptography is the science of securing information using mathematical algorithms and keys, ensuring that only authorised parties can read it. We often get messages from bank on our mobile saying that ‘the message is 128-bit encrypted’. This is classical cryptography, and its security is not unbreakable. Quantum cryptography exploits the properties of quantum mechanics, rather than difficult math problems, to protect data and guarantees the security of communications. Quantum physics is also behind the development of more sensitive and powerful quantum sensors.

Major strides are being taken in the development of quantum computers. In classical computers, the basic unit of information is a *bit*. A *bit* can be in a state of either ‘0’ or ‘1’, which is implemented by setting a transistor either ‘off’ or ‘on’. In a quantum computer, the basic unit of information is a *quantum bit* or *qubit*, which is implemented by a quantum object, rather than a transistor, that follows the principles of *superposition* and *entanglement*. Because of the *superposition* principle a *qubit* can be in the ‘0’ state and the ‘1’ state simultaneously. Quantum principles of *superposition* and *entanglement* ensure building of quantum computers allowing vastly faster solutions for specific complex problems compared to classical computers.

A glimpse of the power of a quantum computer was shown by Google using a 54-*qubit* quantum computer vis-à-vis a classical supercomputer, which has tens of billions of *bits*. In 2019, Google performed a calculation with this quantum computer in 200 seconds; they estimated that the same calculation would take even the best classical supercomputer ~10,000 years to complete [11].

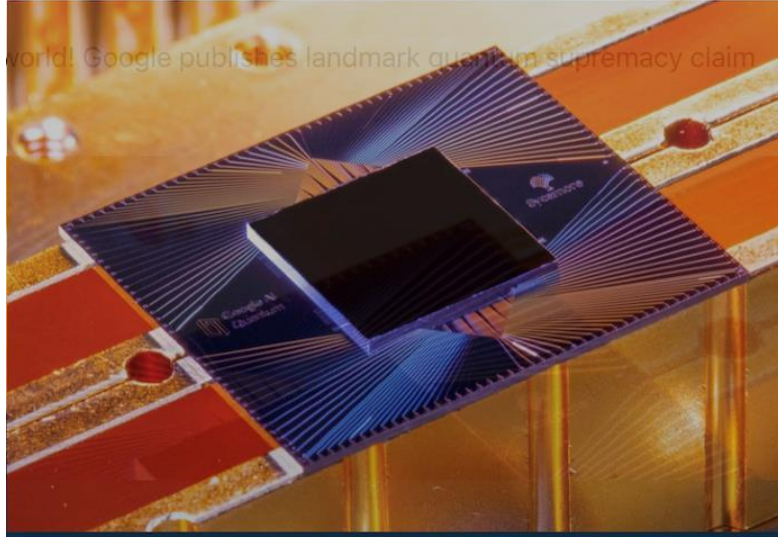


Figure1. Photograph of the 54-qubit Google Sycamore quantum processor. The central chip is about 10 mm x10 mm. (Taken from [11]).

In 2024, Google used a slightly bigger quantum computer (105-*qubit* Willow quantum processor) and performed a standard benchmark computation in under five minutes that would take one of today's fastest supercomputers 10 septillion (that is,  $10^{25}$ ) years — a number that vastly exceeds the age of the universe. This is a comparison between tens of billions of *bits* in a classical computer and  $\sim 100$  *qubits* in a quantum computer. While classical computers have taken about a century to reach the current state, quantum computers have not even completed three decades of their journey, still not mature, but hold great promise for the future.

As mentioned earlier, a qubit can be implemented by a quantum object, such as an atom, say by designating its ground state as '0' and an excited state as '1'. The qubit is a quantum state ( $\psi$ ) which is in a superposition of '0' state and '1' state. Mathematically, (in the ket notation) it is written as,

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

where  $\alpha$  and  $\beta$  are called probability amplitudes.  $\alpha^2$  and  $\beta^2$  is the probability of occupation of the  $|0\rangle$  state and the  $|1\rangle$  state respectively. The total probability is normalised to 1:

$$\alpha^2 + \beta^2 = 1 \quad (2)$$

Microscopic objects, such as an atom, an ion, an electron etc. are quantum systems which obey quantum mechanics. A two-level quantum system can be used as a *qubit*, and a quantum computer can be built by implementing qubits from these microscopic objects. However, in mid-1980s, it was shown that even a macroscopic object, such as an electric circuit, can also obey quantum mechanics. In fact, the 2025 Physics Nobel Prize was awarded for this discovery to John Clarke, Michel H. Devoret and John M. Martinis. Such an electrical circuit,

built with a superconducting material, was shown to have quantised energies like an atom [12], and show another quantum behaviour called quantum tunnelling [13]. This electric circuit, made with superconducting materials and behaving quantum mechanically like an ‘artificial atom’, is called a *superconducting quantum circuit* and it works as a *qubit* which is known as a *superconducting qubit*. Google’s quantum computers are built with *superconducting qubits*. One of the 2025 Nobel Laureates, John M. Martinis was the team leader in building the Google superconducting quantum computer in 2019.

A *superconducting qubit* is basically an *LC* resonant circuit, with a resonance (angular) frequency  $\omega$ , which is related to the linear frequency  $f$  by  $\omega = 2\pi f$  [14].

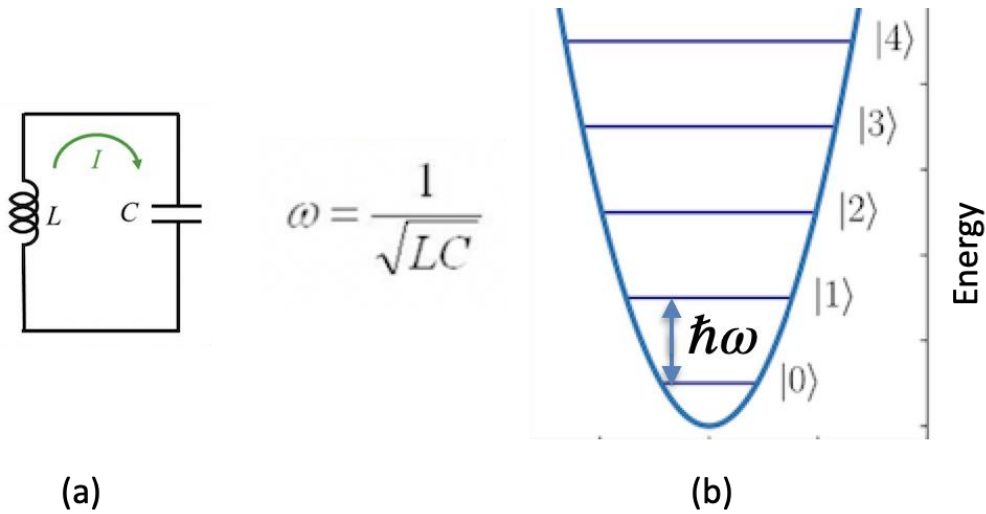


Figure.2. (a) An *LC* circuit where  $L$  is the inductance of an inductor and  $C$  is the capacitance of a capacitor; once a current ( $I$ ) is set in the circuit, it oscillates back and forth with a frequency  $\omega$ , (b) a quantum harmonic oscillator with energy separation  $\hbar\omega$  between successive energy levels.

We know that an *LC* circuit (Fig.2(a)) behaves like a classical harmonic oscillator. However, it can be converted into a quantum harmonic oscillator by choosing appropriate smaller values of  $L$  and  $C$  by lithographic fabrication so that the separation between the successive energy levels,  $\hbar\omega$  (or  $hf$ ) is significantly large for the energy levels to be considered as discrete. These discrete energy levels of a quantum harmonic oscillator within its parabolic potential are shown in Fig.2(b). For a *superconducting quantum bit*, the circuit parameters are chosen such that the energy separation  $\hbar\omega$  falls in the microwave region of the electromagnetic radiation spectrum. A microwave photon of frequency  $f$  ( $= \omega/2\pi$ ) from a microwave electronic module is then used for interactions between the states. As mentioned earlier a *qubit* is a two-level quantum system. We need to choose only two levels, usually the lowest two,  $|0\rangle$  and  $|1\rangle$ , of the quantum harmonic oscillator. As the energy level separations are all equal, it is not possible to ensure that the microwave photon is not causing transitions between  $|1\rangle$  and  $|2\rangle$ , or  $|2\rangle$  and  $|3\rangle$ , ... etc. So, it is not possible to ensure that we

are working with only the  $|0\rangle$  and the  $|1\rangle$  states. The solution comes from a modification of the  $LC$  circuit.

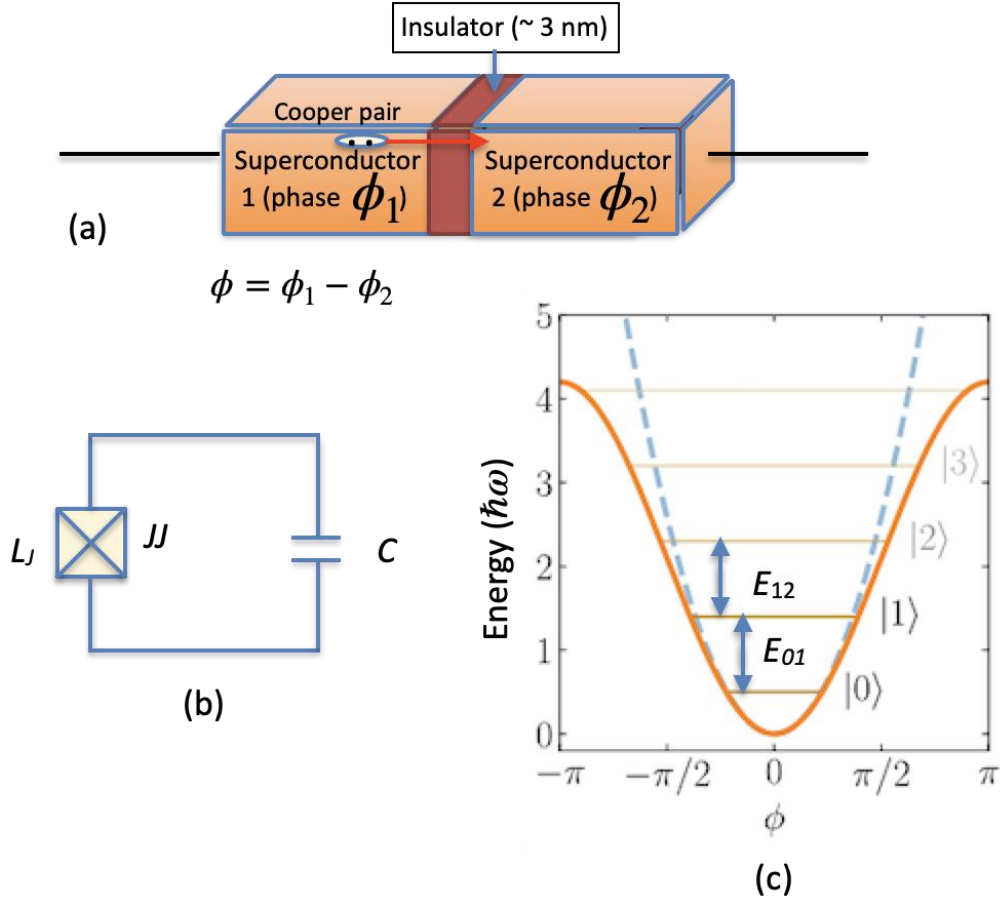


Figure 3 (a) Structure of a Josephson junction ( $JJ$ ) with two superconductors, separated by a thin insulating layer, (b) an electrical circuit with a  $JJ$  and a capacitor, (c) the anharmonic potential energy curve (solid line) of the circuit in (b) and the discrete energy levels.

The linear inductance  $L$  of an ordinary  $LC$  circuit is replaced by a nonlinear inductance in the  $LC$  circuit of the *qubit*. This nonlinear inductance is provided by a device called Josephson junction ( $JJ$ ), which is typically a tunnel junction built with two pieces of superconducting materials joined together with a very thin insulating material, as schematically shown in Fig. 3(a). In a superconductor, the current carrier is not individual electrons; flow of electron-electron bound pairs, called Cooper pairs, are responsible for current flow in a superconductor. In a Josephson junction, Cooper pairs tunnel from one superconductor into another through the insulating layer via quantum tunnelling. The behaviours of Josephson junctions are described by two Josephson equations. Through these Josephson equations, it can be shown that the Josephson junction acts like a nonlinear inductance ( $L_J$ ). The modified circuit with a  $JJ$  is shown in Fig. 3(b).

A superconductor is a macroscopic quantum system. It operates via a collective quantum state where trillions of electrons form Cooper pairs acting as a single coherent wavefunction, and a single quantum phase ( $\phi$ ) describes the whole superconductor. The two pieces of superconductors in a  $JJ$  are described by the phases  $\phi_1$  and  $\phi_2$ . The phase difference  $\phi = \phi_1 - \phi_2$  determines the physics of the  $JJ$  and modifies the potential energy, consequently modifying the harmonic oscillator potential (dashed curve) to an anharmonic potential (continuous curve), as shown in Fig. 3(c). The consequences of this modification are that the energy differences between successive levels are not equal:  $E_{01} > E_{12} > E_{23}$  etc. This ensures that a microwave photon of energy  $\hbar\omega = E_{01}$  cannot couple any other pair of states than  $|0\rangle$  and  $|1\rangle$ , and that we are effectively working with a two-level system, which is the requirement for a *qubit*. The microwave frequency corresponding to  $E_{01}$  is typically about 5 GHz.

Another concern is that to begin with we have to ensure that the qubit is in the  $|0\rangle$  state, which is called initialisation. However, it is not possible if the *qubit* is kept at room temperature. At room temperature, most of the higher states even up to  $|100\rangle$  will have significant probabilities of occupation (given by Boltzmann distribution). So, the *qubit* needs to be cooled down to near-absolute-zero temperature to ensure that it is in the  $|0\rangle$  state. Microwave pulses can then be applied for various quantum operations involving  $|0\rangle$  and  $|1\rangle$  states. Microwave pulses are also used to control *superposition* and *entanglement*, and operation of quantum gates.

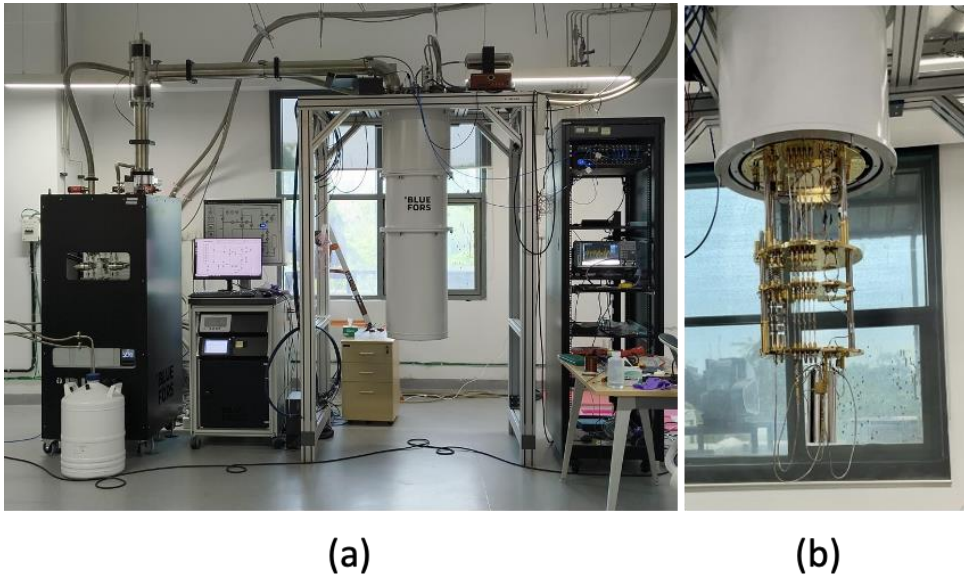


Figure 4 (a) The superconducting quantum computer at TCG CREST. The white object marked “BLUEFORS” is a dilution refrigerator that produces ultralow temperature (10 mK) inside, (b) the inside of the dilution refrigerator: temperature is 10 mK at the bottom plate; the quantum processor is thermally connected to this plate, but inside the cylindrical magnetic shield.

At TCG CREST, we began to build a superconducting quantum computer in 2023. This facility is shown in Fig. 4. The white hanging cylindrical object in Fig.4(a) is a dilution refrigerator, which produces 10 millikelvin ( $-273.14\text{ }^{\circ}\text{C}$ ) temperature, just 0.01 degree above absolute zero ( $-273.15\text{ }^{\circ}\text{C}$ ), using a mixture of  $^4\text{He}$  and  $^3\text{He}$  gases (stored in cylinders hidden inside the black box on the left). The rack on the right contains electronic modules including microwave modules that send signals to the quantum processor through the top connectors on the dilution refrigerator. To hold that low temperature, the cylinder of the dilution refrigerator is evacuated. When four jackets of the dilution refrigerator are removed, one can see the inside structure (Fig.4(b)). There are various electrical connections and cryogenic electronic components. The bottom plate is cooled down to 10 mK. The quantum processor (containing qubits) is attached to this cold plate and enclosed by the shiny cylinder, which is a magnetic shield. The quantum systems are very fragile and even the earth's magnetic field can disturb it. The shield provides protection from the earth's magnetic field.

Our current state of development involves a small (5-qubit) superconducting quantum computer. Companies like Google and IBM quantum computers work with a couple of hundred qubits or even fewer. Although quantum computing promises unprecedented speed, today's quantum computers face many challenges while trying to move from infancy to adolescence. The major challenge comes from the relatively short lifetime (decoherence time) of *qubits*. A quantum system can preserve its quantum state if it is completely isolated from the environment. However, its interaction with its environment causes it to lose coherence, or superposition, within a short time. The environment of a qubit (in general, any quantum system) is defined by any external system (such as, heat, magnetic field, electromagnetic radiation etc.) that interacts with it causing noise, decoherence and information loss. The decoherence time of *superconducting qubits* is typically tens of microseconds.

Between the two Google quantum computers discussed above, the average decoherence time of the *qubits* of the Sycamore quantum processor was 20 microseconds, while that of the more powerful Willow quantum processor was about 100 microseconds. The superiority of the Willow processor comes not only from the approximately double the number of *qubits*, but also from the enhanced decoherence time of the *qubits*. Achieving high-coherence (i.e., longer decoherence time) superconducting *qubits* requires improvement in nanofabrication methods as well as choice of materials [15]. Research on the superconducting materials used for the fabrication of *qubits* is of utmost importance. With the objective of enhancing qubit decoherence time, our work also involves newer superconducting materials [16].

#### **4. Challenges, Prospects and Promises of Quantum Computers**

Building reliable, fault-tolerant quantum computers remains a challenge because qubits are highly sensitive to environmental interference. Scaling up quantum computers to a large number of qubits, required for complex real-world applications, remains a primary hurdle. Experts believe that qubit technologies under various platforms (superconducting, trapped ions, neutral atoms) are advancing rapidly towards producing scalable, reliable, fault-tolerant quantum computers within the next decade.

Quantum computers can unlock advancements in various areas:

- Healthcare: Quantum computers can simulate molecular interactions at an atomic level speeding up the development of new medicines and vaccines.
- Materials Science and Energy: It would be possible to design new materials via quantum simulation for superior batteries or solar cells assisting in climate change mitigation, or even design superconducting materials that would transmit electricity at atmospheric condition without any power loss.
- Logistics and Transportation: Quantum computing can optimise global supply chains, financial portfolio optimization, and traffic flow in real-time.
- Artificial Intelligence: Quantum computing can train more powerful AI models, improving decision-making and automation. It can enhance machine learning models for faster training.

Current quantum computers have limitations in solving real-world problems. As the technology advances, real-world applications will continue to expand over time. Major commercial quantum computer developers are now increasingly confident that commercially relevant quantum computers based on superconducting technology will become available by the end of this decade. In conclusion, quantum physics transitioned from foundational theory to transformative technology and has already made and will continue to make profound impact on the human society.

## Acknowledgements

This article is a tribute to Prof. Arun Kumar Basak, my teacher at Rajshahi University, on the auspicious occasion of his 85<sup>th</sup> birthday. It is time to reflect upon Prof. Basak's remarkable intellectual and humanitarian legacy he has built and continues to build. I am very delighted that Prof. Basak remains an active physicist even at this age. Perhaps his devotion is getting passed on to generations. The setting up of the quantum computer at TCG CREST, Kolkata would not have been possible without my younger colleague, Dr. Snehal Mandal and the doctoral students, Biplab Biswas and Ayan Kumar Ghosh, who are eagerly learning and contributing towards further development.

## References

- [1] Planck, M. (1901). On the law of distribution of energy in the normal spectrum, *Ann. Phys.*, 309, 553 – 563.
- [2] Bohr, N. (1913). On the constitution of atoms and molecules, *Philos. Mag. Ser. 6*, 26, 1 – 25.
- [3] Heisenberg, W. (1925). On the quantum-theoretical reinterpretation of kinematical and mechanical relationships, *Zeitschrift für Physik*, 33, 879-893.
- [4] Schrödinger, E. (1926). Quantization as a problem of proper values, *Ann. Phys.*, 79, 361 – 376.
- [5] Bloch, F. (1929). On the quantum mechanics of electrons in crystal lattices, *Zeitschrift für Physik*, 52, 555-600.

- [6] Bardeen, J., Brattain, W. H. (1948). The transistor, a semi-conductor triode, *Physical Review*, 74(2), 230-231.
- [7] Binnig, G. and Rohrer, H. (1987). Scanning tunneling microscopy-from birth to adolescence, *Reviews of Modern Physics*, 59(3), 615 – 625.
- [8] Goswami, D. K., Satpati, B., Satyam, P. V., and Dev, B. N. (2003). Growth of self-assembled nanostructures by molecular beam epitaxy, *Current Science*, 84(7), 903 – 910.
- [9] Ashoori, R. C. (1996). Electrons in artificial atoms, *Nature*, 379, 413 – 419.
- [10] Faist, J., Capasso, F., Sivco, D.L., Sirtori, C., Hutchinson, A.L. and Cho, A.Y. (1994). Quantum Cascade Laser, *Science*, 264, 553 – 556.
- [11] Arute, F. *et al.* (2019). Quantum supremacy using a programmable superconducting processor, *Nature*, 574, 505 – 510.
- [12] Martinis, J. M., Devoret, M. H., and Clarke, J. (1985). Energy-level quantization in the zero-voltage state of a current-biased Josephson junction, *Phys. Rev. Lett.*, 55(15), 1543 – 1546.
- [13] Devoret, M. H., Martinis, J. M., and Clarke, J. (1985). Measurements of macroscopic quantum tunneling out of the zero-voltage state of a current-biased Josephson junction, *Phys. Rev. Lett*, 55(18), 1908 – 1911.
- [14] Devoret, M. H., Wallraff, A., and Martinis, J. M. (2004). Superconducting qubits: A short review, *arXiv:cond-mat/0411174*.
- [15] Siddiqi, I. (2021). Engineering high-coherence superconducting qubits, *Nature Reviews Materials*, 6(10), 875.
- [16] Mandal, S., Biswas, B., Purkait, S., Roy, A., Satpati, B., Das, I., and Dev, B. N. (2025). Two superconducting thin films systems with potential integration of different quantum functionalities, *Mater. Quantum Technol.*, 5, 026001.