HK Institute of Quantum Science & Technology
香港量子研究院

The Institute, consisting of internationally leading physicists, computer scientists, mathematicians and engineers, will provide a multi-disciplinary scientific research platform at the University of Hong Kong. We will unleash the full potential of the quantum laws of nature to develop powerful new technologies and drive future economies to benefit the national and local economies.

Quantum Science

Quantum mechanics stands out as one of the most important breakthroughs of 20th century science. It has been successfully employed to explain a vast range of phenomena that could not be understood with the traditional laws of classical physics. It provides the foundation for our understanding of the structure of matter, from elementary particles to atoms, molecules, and materials, such as semiconductors, which had an enormous impact on industry and society.

The laws of the quantum physics are very different from the familiar laws of classical physics. In classical physics, the position and the velocity of every particle can be determined with arbitrary precision. In quantum physics, they cannot. As a result, quantum particles can be in a new type of states, in which the position (or the velocity) is not well defined. These states are called *quantum superpositions,* and are the origin many surprising phenomena that are far from our everyday experience. For example, a quantum particle can sometimes behave as if it were in two places at the same time, and can propagate through space as a wave, similar to light.

Quantum superposition has a profound impact on our understanding of physics. At the same time, it brings a revolution in our information technologies. Nowadays, most of our computer and communication technologies are based on the notion of *bit,* an elementary unit of information that can be in two alternative states: either 0 or 1. At the most fundamental level, however, every physical system is made of quantum particles, and can be in a superposition state. A *quantum bit* (or *qubit*) can be not only in the states 0 and 1, but also in an infinite number of intermediate states, corresponding to quantum superposition of 0 and 1. This new type of states offers more room for computing and new possibilities for communication, paving a way for a powerful new generation of quantum information technologies.

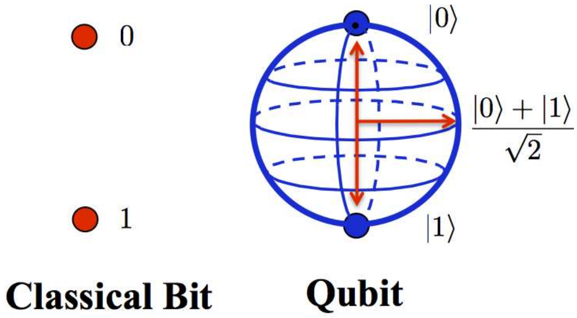

Figure 1. Comparison between a classical bit and a quantum bit (qubit). The classical bit can take two discrete values 0 and 1, whereas a qubit can be in infinitely many states, corresponding to quantum superpositions of 0 and 1. These quantum superpositions can be visualized as points on a sphere, where 0 and 1 are located on the north and south poles.

The power of quantum information is revealed even more clearly when many qubits are combined together. In this case, quantum superposition gives rise to another intriguing feature, called *quantum entanglement*. When two particles, such as a pair of photons or electrons, become entangled, they can remain connected even when separated by a large distance. If the particles are measured, the results of the measurements show some strong correlations that could not explained by classical physics. Einstein was puzzled by these correlations, which seemed to imply some "spooky action at distance" whereby one particle can affect the other instantaneously. By now, we know that these correlations are present in nature, and, if properly exploited and engineered, they can revolutionize our information technologies. The impact of quantum correlations is so important that the 2022 Physics Nobel Prize was given to the scientists who pioneered the first experiments on quantum entanglement.

Quantum Technology

Throughout history, our everyday life has been transformed by the conscious applications of physical laws. In the nineteenth century, Newton's laws and later thermodynamics gave rise to the development of heat engines and railways, which were the driving forces of the industrial revolution. In the twentieth century, the application of Maxwell's equations, through electricity and electronics, enabled the communication of words and pictures at the speed of light through electromagnetic waves.

The discovery of quantum mechanics brought us to the "first quantum revolution"; beginning in the second half of the twentieth century, innovations occurred at an unprecedented level of acceleration, with transistors, microelectronics, lasers and optoelectronics becoming the foundations of today's digital society.

Unfortunately, it is now widely acknowledged in the semi-conductor industry that this five-decade dream run based on silicon technology is coming to an end because of the fundamental difficulties in further shrinking the size of silicon microelectronics and reducing power consumption in conventional computing. Quantum effects begin to interfere in the functioning of electronic devices as they are made smaller and smaller, and eventually the principles of classical information processing will cease to apply.

The Second Quantum Revolution:

Fortunately, the crisis also presents us with the opportunity to usher in the "second quantum revolution", the impacts of which will be truly revolutionary.

- ***Quantum information processing and quantum computing***

In classical computers, data are stored and processed based on binary logic, i.e. the basic information unit is a bit that can be in the states 0 and 1, and the basic operations are logical operations that shuffle 0s into 1s and vice-versa. On the other hand, a quantum computer uses qubits for its computations, and therefore it can potentially access infinitely many states and operations. The expanded possibilities of quantum computers make them hard to simulate using classical computers. Due to the presence of superpositions, every qubit in a quantum computer requires at least two classical bits in the corresponding classical simulator. This means that a quantum computer with just one extra bit is twice as hard to simulate on a classical computer. The complexity of the simulation scales exponentially: 10 qubits require at least $2^{10} \approx 1000$ classical bits, and 1,000 qubits require at least $2^{1000} \approx 10^{300}$ classical bits, which would be much more powerful than any supercomputers in the world. Hence, quantum computing will deliver an exponential

> Encryption usually involves the factorization of a very large number into two large prime numbers. It is computationally easy to generate two fairly large prime numbers and to multiply them together, to form a very large number. As an example, we consider two five-digit prime numbers, 40637 and 72169, whose product gives a ten-digit number 2932731653 through a straightforward computation. However, the factorization of the ten-digit number back to the two five-digit factors will take much longer time to compute. Multiplying two numbers is a mathematically easy problem, and it scales well for the bigger numbers. However, factoring very large numbers is extremely time consuming. On current computers factoring numbers with 300 digits would take hundreds of thousands of years.

advantage for certain classes of problems, such as factoring very large numbers, a problem that has profound implications for cybersecurity.

Quantum computing can exponentially speed up the simulation of molecular dynamics, thus contributing to a dramatic speed-up in the design of new drugs and new molecules. Quantum materials can lead to smaller electronics devices, new ways of encoding, storing and processing information, thus enabling quantum computing. Quantum cryptography can lead to information-theoretic secure communication, thus achieving the holy grail of communication security. (See Figure 3 (left)) IT firms such as Google, Intel, Microsoft, Amazon, IBM and Alibaba are investing heavily in quantum computing. Google recently announced achieving "quantum supremacy"; for a specific computational task, its quantum processors could perform better than those of conventional computers. See Figure 1 (right). It is anticipated that an entirely new economy will be constructed from the above transformative technologies. This will revolutionize the world as we know it. Nonetheless, many deep scientific and engineering challenges need to be overcome before such a vision can become a reality.

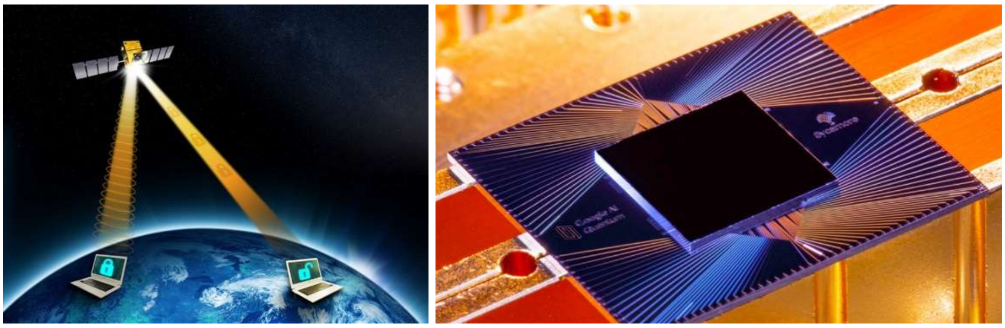

Figure 2: (left) Quantum communication via satellite. (right) Google’s quantum chip.

- ***Quantum communication***

Nowadays, sensitive data is usually encrypted and then delivered through optical fibers and other channels together with the digital keys needed to decode the information. The data and the keys are both sent as classical bits—a sequence of data consisting of 1s and 0s. Both data and keys might be eavesdropped and copied during the transit without leaving a trace, thus making the security vulnerable. Quantum communication takes advantage of the laws of quantum physics to protect data. In quantum communications, the photons employed for transmitting data along optical fibers are represented by superposed qubit states, meaning that they are combinations of 1 and 0 simultaneously. If a hacker tries to observe them in transit, the quantum state would collapse the qubit to either 1 or 0 (i.e. the classical bit), hence damaging the quantum information and make it detectable by the receiver. These principles have already been implemented in commercial applications, such as securing bank transactions, internet communications, and other highly sensitive data. China is now leading the way to the development of large-scale quantum networks for secure communication, both nationally and globally.

Mission and Vision

The institute will bring together leading physicists, engineers, computer scientists and mathematicians to work on the research frontiers of quantum science and technology, including quantum information, quantum materials, and quantum AI and their applications. The institute will not only provide world-class platform to carry out both theoretical and experimental research, but also establish strong exchange and visitors’ programs both internationally and with mainland China.

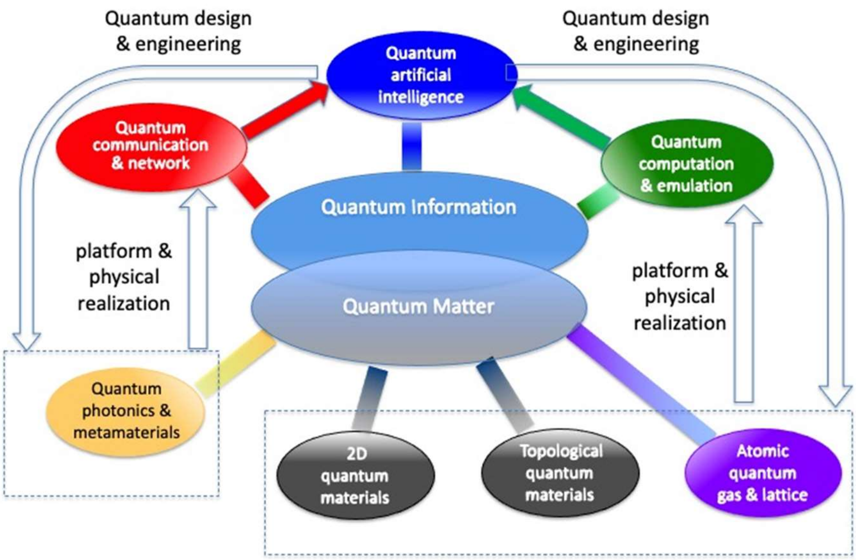

Figure 3: Existing strength related to quantum study at HKU that will be linked and dramatically expanded upon by the Institute.

Grand challenges to tackle:

A) Building a secure Quantum Internet

MIT Technological Review has chosen a hackable quantum internet as the number 1 breakthrough technology. Going beyond that, professors at HKU are currently building unbreakable quantum codes and working towards an unhackable quantum internet, which may lead to reliable quantum networks and eventually quantum clouds.

B) Quantum Matter for Quantum Computing

At the hardware level, novel platforms such as exotic quantum materials, quantum gases and lattices, and metamaterials will be needed to implement the fundamental quantum computing units. Professors in the institute have been leading an Area of Excellence (AoE) project to explore novel quantum materials in the atomically thin limit and the effort in metamaterial platforms.

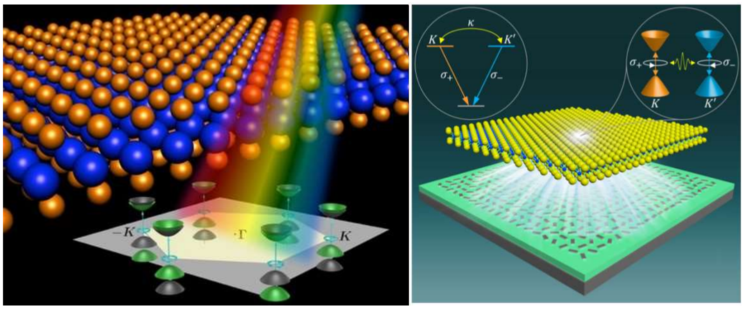

Figure 4: Quantum hardware platforms. Left: Atomically thin quantum materials host versatile quantum degrees of freedom that can be optically accessed as information carriers. Right: A quantum interface between optical quantum information in meta-surface and electronic quantum information in quantum matters.

C) Quantum AI and Quantum Machine Learning

Quantum software will unleash the full power of quantum computing in implementing AI algorithms. AI based on Quantum principles will greatly outperform classical AI algorithms currently used in various applications, such as robotics, vision, and language processing, in terms of efficiency and speed. Professors here are working on quantum AI and quantum machine learning, and exploring the power and limitations of quantum algorithms.

D) Quantum Sensor, Measurement and Metrology

Quantum science-enabled technologies have demonstrated their great advantages in precision measurement. Yet grand challenges remain to overcome the ultimate noises produced by quantum fluctuations, to define technological pathways for searching elusive dark matters or, as simple as a task to detect molecular threats or contaminants at extremely low concentrations. Leveraging quantum theory and harnessing new quantum technologies such as synchronized atomic clocks, comb lasers, atomic ensembles and solid-state atom-like systems will allow the best measurements with quantum advantages.

Appendices:

A. **Institute Structure**:

- The institute involves Regular Members from HKU, as well as Associate Members from other sister institutions

- Run International Visitors Programs and Seminars Series, International exchange students program, joint postdocs, joint Ph.Ds *etc*. Prestigious postdoctoral fellowships and graduate scholarships will be created possibly under donors' name
- The academic activities will be overseen and advised by an Advisory Committee consisting of world-class scientists in quantum science and technology as members and to be chaired by a Nobel Laureate Sir Prof. Tony Leggett

B. Existing Strength and Achievements:

- Over 20 leading experts in quantum science and technology and closely related fields (having been invited) as principal investigators (PIs), with **5** being among the 2022 list of "Highly Cited Researchers" of Clarivate Analytics
- Outstanding research recognized by prestigious international and national awards and honors
- Active participation in the strategic plan of The Quantum Science Center of Guangdong-Hong Kong-Macao Greater Bay Area
- Versatile research-supporting platforms, including Key Laboratories in Area of Excellence at Hong Kong and Guangdong-Hong Kong Joint Laboratory of Quantum Matter

C. Research initiatives and activities

Quantum Materials Research

- 2D quantum materials and devices
- Quantum photonics and metamaterials
- Topological quantum materials and devices
- Atomic quantum gases and lattices

Quantum Information Research

- Quantum communication and quantum network
- Quantum computation and quantum emulation
- Quantum artificial intelligence including quantum machine learning
- Quantum sensing and metrology