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In the age of quantum information and computation: What lies ahead?

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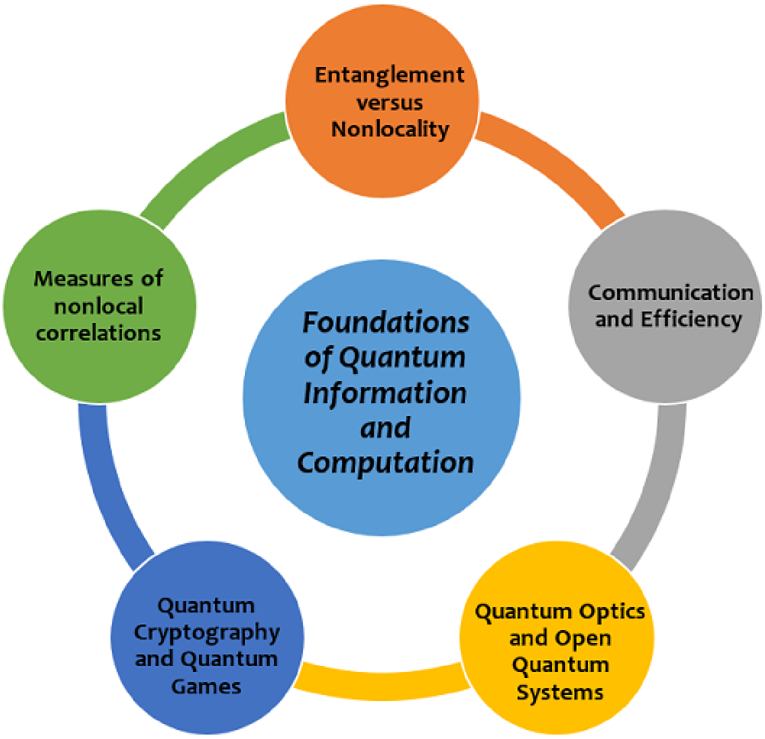
In-Focus

With the limitation of classical mechanics to explain phenomena such as black-body radiation, photoelectric effect, emission spectra of atoms, and structure of atoms- the first three decades of twentieth century witnessed a period of turmoil, excitement, and creative intellect to accept the need to replace the existing theories and to introduce a new theory for a complete mathematical description of the physical world. Subsequently, Erwin Schrödinger and Werner Heisenberg proposed a mathematical framework of the new quantum theory independently using wave mechanics and matrix mechanics, respectively. Since then, Quantum Mechanics has emerged as a fundamental ingredient for understanding various facets of nature such as atomic and sub-atomic physics, quantum optics and a plethora of phenomena in condensed matter physics. Modern developments in computing could be said to have started from the work of Alan Turing, while information theory was put on the pedestal of modern science by the efforts of Claude Shannon. The amalgamation of quantum physics with computing and information theory could be historically traced from the works of Einstein, Podolsky and Rosen (EPR), followed by that of John Bell and culminating in efforts made by Charles Bennett. This was further cemented by the efforts of William Wootters. The EPR paradox paved the way for several open-ended discussions, studies and debates to understand and analyse quantum correlations, described by quantum mechanics as against the description provided by local hidden variable (LHV) theories. Experimental developments over the last few decades have brought the subject of quantum information and computation to the threshold of technology development.

The advent of quantum information and computation promises an effective and secure mechanism of storing, manipulating, and transmitting information based on the fundamental laws of quantum mechanics. Similar to a bit- a fundamental unit of classical computation- A qubit is the fundamental unit of quantum computation. Unlike a bit which can exist only in one of the two possible states 0 or 1, a qubit can exist in an arbitrary linear superposition of 0 and 1, $|\psi\rangle = a|0\rangle + b|1\rangle$ the state of a qubit can be represented as where are complex numbers in a two-dimensional complex vector space, $|\psi\rangle$ is a mathematical description of the state of a qubit, and $|\ \rangle$ signifies a 'Ket vector' representing a quantum state. The physical realization of a qubit can be understood in terms of an electron, a photon, an atom or a very cold superconducting circuit. For two or more than two qubits superposition principle, in specific cases, leads to entangled quantum systems- Cynosure of most of the phenomena in quantum information and computation. Apart from addressing and satisfying the quest to understand the foundations of quantum mechanics, quantum entanglement has also been extensively used as an effective resource for several potential applications such as dense coding, teleportation, secret sharing, quantum algorithms, quantum key distribution and quantum cryptography, quantum games, quantum communication etc. In the last three decades, the existence of long-range quantum correlations between entangled particles has been established as a factor responsible for achieving efficient, secure and optimal communication in comparison to its classical counterpart. In fact, recent studies have shown that separable systems exhibiting quantum correlations- as captured by a measure known as quantum discord- can also be used for efficient quantum information and computation. In a nutshell, nonlocal or quantum correlations existing between particles give an edge to quantum computation over classical computation.

On the implementation front, a quantum computer is required to deal with quantum complexity and quantum error correction from the perspective of scalability. With the increase in the number of qubits; controlling, processing, and accessing quantum information becomes much more intricate due to the uncontrollable interactions of the original quantum system with its surroundings- the characteristic trait of complexity. Unfortunately quantum error correction involves huge expense in terms of number of qubits and quantum gates, thus scalability is a major issue to be addressed before one can have a fault tolerant quantum computer. Clearly, there are many tech giants working to address technological challenges in addition to academicians analysing the theoretical and experimental challenges up front. Some of the top companies and research labs include IBM, Google, Microsoft, D-Wave, Intel, Regetti, Hewlett Packard, Ion Q, Cambridge quantum computing and Quantum Biosystems, to name a few. IBM has provided an online platform to experience prototypes of quantum computers and to contribute to the State-of-the-Art. Google has recently announced what they termed as Quantum Supremacy, only to be rejected by IBM a couple of days later. The D-wave company introduced a 2000-qubit quantum computer based on quantum annealing. The D-wave machine, however, is not a circuit based machine but a noisy version of an adiabatic quantum computer. Nevertheless, there is progress and there is a way forward!



Some aspects of quantum information and computation, to which the interdisciplinary research group at IIT Jodhpur is actively contributing to through various research projects.

The interdisciplinary research group in Quantum Information and Computation (QIC) at IIT Jodhpur works towards establishing a convergence between diverse academic spaces. In this interdisciplinary joint collaboration, we study quantum correlations in non-classical states from the perspective of a practical interface between quantum optics and quantum information processing. Such correlations occupy a central position in the quest for understanding and harvesting the power of quantum computing and fundamentals of quantum information processing. Another problem of particular interest is to analyse and characterize multi-qubit entangled states for establishing shared communication networks among multiple users. In order to deal with issues of decoherence, the group makes systematic use of open quantum systems to study various facets of quantum information and computation, including the analysis of efficacies of quantum resources.

The Faculty Members in the group are involved in Government of India-funded projects on Quantum Information and Computation of approximately Rs. 3.45 crore ranging from classification and quantification of multi-qubit entangled states to generation of multi-qubit entangled states to heat engines. Further, the group routinely organizes workshops and conferences to enable conversations and collaborations. The QIC group also organizes Faculty development programs for knowledge dissemination. At present, Atul Kumar, Department of Chemistry; Subhashish Banerjee and V. Narayanan, Department of Physics; Kirankumar Hiremath and Vivek Vijay, Department of Mathematics; Suman Kundu and Debasis Das, Department of Computer Science and Engineering; Mahesh Kumar and Harshit Agrawal, Department of Electrical Engineering; and B. Ravindra, Department of Mechanical Engineering are actively contributing towards development of the Interdisciplinary Research Platform- QIC at IIT Jodhpur.

From the perspective of academic programs, the group offers a Ph.D. program in Quantum Information and Computation to interested students. Further, the group has also proposed a specialization in QIC to B.Tech. students which will allow them to complete a minimum of 20 credits through compulsory and elective courses. The courses will be integrated with online quantum experience platforms so that students can learn as well as contribute to the state of the art.

Quantum Information and Computation offers potential applications that are otherwise not possible using classical computation. Although a fault tolerant scalable quantum computer is considered as a distant dream, once implemented, it promises exciting possibilities in security, computing, finance, drug and material, and computational chemistry. One may consider teleportation between ground and space, establishment of mobile quantum satellite station for quantum key distribution, dealing with quantum devices in noisy intermediate-scale quantum (NISQ) era, developments in post quantum cryptography period, estimation of ground-state energy of hydrogen molecule, Lithium and Beryllium Hydride and simulating water molecule using variational quantum eigensolver (VQE) coupled with classical optimization algorithm to evaluate its ground state as small steps towards future. Definitely, the accuracy of calculations depends on adding and handling more quantum resources with algorithms running for a longer time. Nonetheless, the classical and quantum machines will definitely co-exist in future with users maximizing the technologies at both ends to the best of their abilities and advantages.

Let's dive into the new computing paradigm where the complexities involved will, in fact, make our life simple!

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