Response to "Request for Information on Quantum Information Science and the Needs of U.S. Industry"

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Summary

IBM Research has had a long history in support of the pursuit of quantum information science (QIS) through industry. All the way back to the early eighties, IBM sponsored the seminal conference in which Richard Feynman discussed the possibility of utilizing quantum mechanics to power a new generation of computers. Since then, major accomplishments by IBM include the first demonstration of a quantum key distribution (Bennett, Smolin 1989), the first realization of Shor's factoring algorithm in an NMR System (Almaden, 2001), and more recently arbitrary quantum error detection in a scalable lattice of superconducting qubits (2015). IBM has committed to pushing towards fault-tolerant quantum computing employing quantum error correction, and has actively engaged and collaborated with the United State federal government to this end. For example, the IBM quantum computing team at TJ Watson Research Center has worked on the IARPA sponsored Multi-Qubit Coherent Operations program since late 2010, and will continue to work complementarily where opportunities arise for further progress. Here we present some of our thoughts on the state of quantum information science, applications in this realm, and our vision of industry's role.

Opportunities

Quantum information science includes, for example, quantum computing and processing, quantum algorithms and programming languages, quantum communications, quantum sensors, quantum devices, single photon sources, and detectors. What areas of pre-competitive QIS research and development appear most promising? What areas should be the highest priorities for Federal investment? What are the emerging frontiers? What methods of monitoring new developments are most effective?

A quick scan of the quantum information science (QIS) landscape currently shows it bolstered upon three pillars of application: quantum computing, quantum communication, and quantum metrology. Arguably, the quantum communication and quantum metrology pillars are the most competitive and already on the path towards commercialization. Quantum key distribution (QKD) networks are already being formed throughout the US and Europe, and the techniques of quantum sensing are being employed by the oil industry. An important breakthrough technology that will push QKD to the next level is the development of quantum repeaters. Reliably spreading out entanglement over long distances with trusted nodes will be critical for such communication networks to take off. Currently, experiments in this field are attempting to tackle it via conversion between hybrid quantum systems, connecting superconducting or solid state qubits to optical degrees of freedom as flying photons to transmit over distance.

The Holy Grail technology in QIS, is the universal quantum computer, which utilizes the potential for exponential speed-up for certain important problems. The most commonly discussed applications for a universal digital quantum computer are Shor's factoring for defeating RSA encryption and other quantum Fourier transform-based algorithms. However, there remains still a large region of untapped promise for universal quantum computing, especially in the realm of digital quantum simulation and finding algorithms to be applied to big data. Digital quantum simulation involves the construction of target Hamiltonian problems from a universal set of gate operations on logical qubits. The potential for this form of digital quantum simulation is to eventually solve problems in physical chemistry: mimicking naturally occurring molecules and chemical compounds, one has the potential to understand the underlying energy structures and dynamics of the compound. This opens the door towards chemical and biological-pharmaceutical design "from the ground up." The details for how this would look at this stage are still incredibly murky, but the tremendous influence and impact this application could have on life and nature is profound enough that this form of quantum computing research must remain a focus throughout industry, academia, and national laboratories.

Along the same lines as the digital quantum simulation is the emerging frontier of analog simulation. For analog quantum simulation, the idea is to directly build in the interactions which may occur in some system (i.e. Ising model, Fermi-Hubbard model, anti-ferromagnetic Heisenberg model) into the physical qubit hardware. Via coupling certain degrees of freedom within the quantum circuitry, it is possible to closely imitate these targeted Hamiltonian systems. Here, we can now use a controllable quantum system to mimic another directly, without breaking it down into a universal set of quantum computing gates, as in the digital quantum simulation case. This has the potential to be lean, as no error correction would be needed if the noise in the simulated system were to closely resemble the noise in a real system. However, there exist major hurdles to the applicability of and usefulness of solutions if that assumption were not the case. This analog simulation realm is likely more near term from a hardware development point of view, as the underlying qubits need not be fault-tolerant, and has the potential to drive new perspectives in quantum theory.

As part of understanding the opportunities within QIS, it is also imperative to have a continuing framework for monitoring developments and new ideas. This is best done through technical exchanges and conferences. A good example is the yearly IARPA sponsored MQCO Technical Exchange Meeting, which pushes on a 'nuts-and-bolts' presentation style across all instantiations of qubits. This qubit agnostic approach allows for the potential for collaboration and recognition of common problems throughout the field. For example, from the most recent January meeting, it became clear that software and electronics development for superconducting qubits, trapped-ions, and spin qubits could all be a common thread of future development. Another important arena for QIS development is to build upon the membership base of the Group of Quantum Information (GQI) within the American Physical Society. GQI already sponsors a large number of talks and events at the APS March meeting each year. However, becoming a division, and encompassing more aspects of QIS will only help bolster communication throughout the community and push more rapidly the research.

Market Areas and Applications

The 2009 "Federal Vision for Quantum Information Science" 1 identified exciting new possibilities for QIS impact, including mineral exploration, medical imaging, and quantum computing. Now, six years later, what market areas do you think would most benefit from quantum information science?

In the long term (10-20 years), QIS has the potential to influence bio-pharmaceutical and material science fields through the simulation of chemical and possibly biological compounds. This is certainly a speculative application and time window, but would have tremendous impact on our society.

"Big Data is the world's natural resource for the next century" - IBM CEO Ginni Rometty

A machine which can potentially search this data or find connections within it would have a tremendous impact on the many industries. Quantum computing has the possibility of doing this faster and more research needs to be done in this direction.

Although code breaking is not to be of commercial interest, security of information is. The application towards this end will require a close concert with federal interests for issues of national security. However, financial institutions and large corporations would all find the ability to both securely transmit and store large amounts of data to be of important application.

A quantum sensor is a signal detecting device that exploits quantum mechanics to achieve sensitivity or resolution that is better than can be achieved using detectors based on classical principles. There are many examples of quantum sensing, ranging from quantum limited amplifiers for measuring small voltages/currents to NV centers for detecting small magnetic fields. There are two classes of quantum sensors. The first employs quantum correlation, such as quantum entanglement, to improve the sensitivity; the second exploits an understanding of quantum physics to control how a system interacts with its environment, to understand it better and ensure that no information is left behind.

Barriers

Funding levels and mechanisms, technology, dissemination of information, and technology transfer are some of the potential barriers to adoption of QIS technology. What do you see as the greatest barriers to advancing important near-term and future applications of QIS? What should be done to address these barriers?

The greatest barriers to advancing important applications of QIS are not having the appropriately aimed programs for research. The goals of the research needs to be directed towards solving specific problems which are impacting the continued progress towards more connected and more coherent quantum networks.

For example, it has become clear to both the superconducting qubit and trapped-ion communities that materials research is an important avenue to pursue. Some of the important materials work is aimed at making better individual qubit devices or individual traps but moving ahead, this will also necessitate materials for constructing large networks of qubits. The community as a whole needs to understand the limits of coherence which will be bolstered through researching materials and interfaces.

Another area of importance is to investigate new quantum algorithms and problems which have the potential for quantum speed-up. Recently, new ideas have emerged to bring quantum speed-up to machine learning algorithms, with the assumption of a quantum RAM. As the hardware continues to improve, a true effort in quantum computer science will be necessary to develop compilers and algorithms that can make use of this hardware.

Finally, it is critical to note that a fully functional universal quantum computer is still a fair way into the future. Many areas still need to remain open to scientific discussion and debate so that information can freely flow to reach the end goals quicker and more efficiently. These will naturally occur through conferences, workshops, and refereed publications. It would be further bolstered through federally-sponsored programs which engage international collaboration and integration between academia, industry, and national laboratories. Furthermore, it will be critical to engage realms outside of the current fields of QIS, tying in engineering and computer science departments, advertising the need for integration of talent to solve problems which arise with scaling quantum networks for quantum computing.

Workforce Needs

Addressing opportunities in QIS and barriers to applications requires a workforce spanning many disciplines, ranging from computer science and information theory to atomic scale manipulation of materials, and possessing a range of knowledge and skills. What knowledge and skills are most important for a workforce capable of addressing the opportunities and barriers? In what areas is the current workforce strong, and in what areas is it weak? What are the best mechanisms for equipping workers with the needed knowledge and skills?

As the field of quantum computing continues to mature on the hardware side, an important next step is working on the integration of the full quantum computing system. Building up larger processors towards the end goal of fault tolerant quantum computing will require a workforce with a wide variety of skills. It is clear however, that the next generation workforce will not be emerging exclusively from those with PhDs in quantum algorithms, condensed matter, or even physics. Rather, with the growing quantum industry exploring applications in QIS, we have to explore building up a quantum engineering discipline in universities. Quantum engineering would refer to a background which contains quantum mechanics, electrical and microwave engineering (strong electromagnetism and circuit background), materials science, computer science, and numerical simulation. These would be the critical skills of a well-rounded individual looking to enter the quantum computing workforce industry. Government research grants supporting university work in these areas will be critical to developing an adequate workforce. Universities will need to interface with industry in order to build up programs which focus on these multi-disciplined areas. This can be achieved through more collaboration and the “sharing” of graduate students or postdocs between industry and a university lab, which can be aided by appropriate government grants and contracts—more NSF GOALI grants, for example, perhaps targeted at key fields.

Another area of exploration for the workforce is to have stronger ties between industry and national labs. Shared work arrangements would help to engage the two sides and help make use of resources which are present in national labs. As an example, in superconducting qubits, there have been numerous collaborations between university groups (UChicago and U Wisconsin) with Argonne National laboratory to explore superconducting resonators and surface spin studies. At IBM, we have actively engaged NIST Boulder, working with David Pappas on understanding new materials and interfaces for improving qubits. It is important for this type of collaboration to continue and be further supported towards a mutual end, diversifying the workplace in both types of institutions.

Finally, attracting the top talent and interest of young individuals to quantum engineering will require outreach through young innovator type workshops. At these workshops, young aspiring minds curious about quantum can see presentations from distinguished speakers from academia, industry, and national labs showcasing the active and thriving QIS field. These summits will serve to demonstrate the vibrant and engaging quantum industrial revolution that is coming upon us.