Quantum Computing:

Challenges and Opportunities

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About the Editor

Michael Erbschloe has worked for over 30 years performing analysis of the economics of information technology, public policy relating to technology, and utilizing technology in reengineering organization processes. He has authored several books on social and management issues of information technology that were published by McGraw Hill and other major publishers. He has also taught at several universities and developed technology-related curriculum. His career has focused on several interrelated areas:

- Technology strategy, analysis, and forecasting
- Teaching and curriculum development
- Writing books and articles
- Publishing and editing
- Public policy analysis and program evaluation

Books by Michael Erbschloe

Threat Level Red: Cybersecurity Research Programs of the
U.S. Government (CRC Press)
Social Media Warfare: Equal Weapons for All (Auerbach Publications)
Walling Out the Insiders: Controlling Access to Improve Organizational
Security (Auerbach Publications)
Physical Security for IT (Elsevier Science)
Trojans, Worms, and Spyware (Butterworth-Heinemann)
Implementing Homeland Security in Enterprise IT (Digital Press)
Guide to Disaster Recovery (Course Technology)
Socially Responsible IT Management (Digital Press)
Information Warfare: How to Survive Cyber Attacks (McGraw Hill)
The Executive's Guide to Privacy Management (McGraw Hill)
Net Privacy: A Guide to Developing & Implementing an e-business
Privacy Plan (McGraw Hill)

Introduction

Quantum computing is based on quantum bits or qubits. Unlike traditional computers, in which bits must have a value of either zero or one, a qubit can represent a zero, a one, or both values simultaneously. Representing information in qubits allows the information to be processed in ways that have no equivalent in classical computing, taking advantage of phenomena such as quantum tunneling and quantum entanglement. As such, quantum computers may theoretically be able to solve certain problems in a few days that would take millions of years on a classical computer.

Quantum computers—a possible future technology that would revolutionize computing by harnessing the bizarre properties of quantum bits, or qubits. Qubits are the quantum analogue to the classical computer bits “0” and “1.” Engineering materials that can function as qubits is technically challenging. Using supercomputers, scientists from the University of Chicago and Argonne National Laboratory predicted possible new qubits built out of strained aluminum nitride. Moreover, the scientists showed that certain newly developed qubits in silicon carbide have unusually long lifetimes.

Quantum computers could break common cryptography techniques, search huge datasets, and simulate quantum systems in a fraction of the time it would take today’s computers. However, engineers first need to harness the properties of quantum bits. Engineering new qubits with less difficult methods could lower one of the significant barriers to scaling quantum computers from small prototypes into larger-scale technologies.

One of the leading methods for creating qubits involves exploiting specific structural atomic defects in diamonds. Using diamonds is both technically challenging and expensive. Now researchers from the University of Chicago and Argonne National Laboratory have suggested an analogous defect in aluminum nitride, which could reduce the difficulty and ultimate cost of manufacturing materials for quantum computing applications. Using the Edison and Mira supercomputers at DOE’s National Energy Research Scientific Computing Center and Argonne National Laboratory respectively, the researchers found that by applying strain to aluminum nitride, they can create structural defects in the material that may be harnessed as qubits similar to those seen in diamonds. They performed their calculations using different levels of theory and the Quantum Espresso and WEST codes, the latter developed at the University of Chicago. The codes allowed them to accurately predict the position of the defect levels in the band-gap of semiconductors. The researchers also closely collaborated with experimentalists to understand

and improve the performance of qubits in industrial materials. Recently, they showed that newly developed qubits in silicon carbide have much longer coherence times than that of the more well-established defect qubits in diamond. Their results pointed to industrially important polyatomic crystals as promising hosts for coherent qubits for scalable quantum devices.

Source: https://science.energy.gov/ascr/highlights/2017/ascr-2017-01-a/

Peter Shor's 1994 breakthrough discovery of a polynomial time quantum algorithm for integer factorization sparked great interest in discovering additional quantum algorithms and developing hardware on which to run them. The subsequent research efforts yielded quantum algorithms offering speedups for widely varying problems, and several promising hardware platforms for quantum computation. These platforms include analog systems (usually cold atoms) used for simulating quantum lattice models from condensed-matter and high-energy physics, quantum annealers for combinatorial optimization, boson samplers, and small-scale noisy prototypes of digital gate-model quantum computers.

In the longer term, the emergence of scalable, fault-tolerant, digital quantum computers offers a new direction for progress in high performance computing as conventional technologies reach their fundamental limitations. Quantum speedups have been discovered for a number of areas of DOE interest, including simulations for chemistry, nuclear and particle physics, and materials science, as well as data analysis and machine learning. In addition, quantum speedups have been discovered for basic primitives of applied mathematics such as linear algebra, integration, optimization, and graph theory. These demonstrate the potential of quantum computers to yield better-scaling methods (in some cases exponentially better) for performing a wide variety of scientific computing tasks. Practical realization of this potential will depend not only on advances in quantum computing hardware but also advances in optimizing languages and compilers to translate these abstract algorithms into concrete sequences of realizable quantum gates, and simulators to test and verify these sequences. The development of such software has recently seen rapid progress, which can be expected to continue given sufficient support.

Source: https://science.energy.gov/~/media/ascr/pdf/programdocuments/docs/ASCRQuantumReport-final.pdf

Imagine typing a very complex query into your computer and having to wait more than a lifetime for results. Thanks to scientists like Davide Venturelli, supercomputers of the future could return those results in a fraction of a second. Davide is a quantum computer research scientist for the Universities Space Research Association. Quantum theory explains how matter acts at the tiniest levels; in applying it to computing, researchers study ways in which that behavior can advance processing power. “We explore how to control these quantum behaviors, to make them happen on demand, in order to crunch numbers and process information,” he says. “We’re pushing the boundaries of what is known in computer science.”

Quantum computer research scientists help to solve problems. In their research, they make scientific assumptions based on quantum theory and then conduct experiments to test whether their solutions work. These scientists may be involved in a variety of projects but often focus on a specific goal. Davide focuses on finding new ways of applying quantum theory to improve how computers solve optimization problems—that is, problems for finding the best of all possible solutions. Digital computers, which are most common today, process information using variables with 1 value (either 0 or 1) at a time. Quantum computers can use both values simultaneously, which results in faster processing. “We know that quantum computers are more powerful than digital computers,” he says, “but we don’t know by how much yet.”

Research. In studying information technology, quantum computer research scientists think about possibilities. For example, Davide asks questions in his research such as, “What is the fastest possible way we can make computers process information?” Davide and other research scientists use their understanding of quantum theory to come up with solutions. Their research may lead to problem-solving computer processes that calculate and sort information much faster. For example, research scientists might develop a theoretical solution that can be run only on quantum computers designed to produce better weather forecasts.

Experiments. To test whether their theories work, quantum computer research scientists may conduct experiments or work with experimental physicists. For example, they may create a quantum environment with computer hardware, then test how particles in that environment react to different levels of laser intensity. Experiments that verify a theory may lead to improvements, such as more efficient computer design and faster, more secure communication for computer networks. But relying on theory means that scientists work with incomplete information—so they’re sometimes surprised at the outcomes. “Experiments may result in the opposite of what you expect,” says Davide, “and you analyze the data to try to figure out why.”

To become a quantum computer research scientist, you usually need a doctoral degree (Ph.D.). But you need some qualities and skills in addition to the formal credential. As researchers, quantum computer research scientists should enjoy being part of a team and sharing their findings with others, which may include engineers, mathematicians, physicists, and Ph.D. students. This collaboration helps bring varied perspectives to solving a problem. “There’s a cross-utilization of ideas when you work with different groups,” Davide says. “My colleagues are very smart and open-minded people.”

Like many scientists, quantum computer research scientists must have strong analytical, critical thinking, and reasoning skills to solve complex problems. Attention to detail is critical as scientists precisely record their theories and experiments, which must be reproducible and able to withstand peer review.

Communication skills are also important. To share their research with collaborators or the public, quantum research scientists must be able to write papers and present their findings at conferences. They may also need to write proposals for grants to fund research projects. Quantum computer research scientists usually need a Ph.D. to learn methods of discovery and to develop the tools needed for researching. Coursework in undergraduate and graduate degree programs typically includes computer science, mathematics, and physics.

You may decide to pursue a master’s degree with classes in quantum computing before entering a Ph.D. program. Davide studied physics at the bachelor’s and master’s levels, but he was passionate about computers, too. Not surprisingly, quantum computing piqued his interest. “It’s a wonderful interaction between the two disciplines,” he says. Davide earned his Ph.D. in nanophysics and numerical simulations of condensed matter.

The U.S. Bureau of Labor Statistics (BLS) does not collect data specifically on quantum computer research scientists. Instead, BLS may count these workers among physicists, of which 15,650 were employed in May 2015. The median annual wage for physicists in colleges, universities, and professional schools—where most quantum computer research scientists are likely to work—was $63,840. That’s more than the median annual wage of $36,200 for all workers.

Quantum computer research scientists work primarily indoors, in academic settings, and may travel frequently to attend seminars or conferences. Area of focus or project type may dictate specific details of their work. For example, testing particularly intricate theories may take days or months, working either independently or with other scientists.

Whether alone or with colleagues, Davide enjoys his work for the independence his job offers. “You have lots of intellectual freedom. Nobody really tells you what to do,” he says. “It’s up to your skills and vision.”

Source: Domingo Angeles, "Quantum computer research scientist," Career Outlook, U.S. Bureau of Labor Statistics, July 2016. https://www.bls.gov/careeroutlook/2016/youre-a-what/quantum-computer-research-scientist.htm

Realizing the Potential of Quantum Information Science and Advancing High-Performance Computing

July 26, 2016 at 6:07 PM ET by Altaf H. (Tof) Carim, William T. (Tim) Polk, and Erin Szulman

The Administration reports on challenges, opportunities, and the path forward in quantum information science, and releases a plan for high-performance computing.

Quantum mechanics describes the behavior and interaction of matter and energy at the scale of individual atoms or subatomic particles. We intuitively understand the collective effects of particles at much larger scales, but quantum behavior can often seem strange and counterintuitive. For example, at the most fundamental level, both matter and radiation (including visible light) behave in some ways like discrete particles and in other ways like continuous waves, resulting in surprising properties. These quantum phenomena include superposition (in which a system simultaneously includes all possible measurement outcomes with some probability, and only has a fixed value once such a measurement takes place) and entanglement (a superposition of the states of multiple particles, in which their properties are correlated with each other). Taking advantage of such properties to process information—working at the intersection of quantum phenomena with information science—provides unique and exciting opportunities in sensing, metrology, navigation, communications, fundamental physics, simulation, new paradigms in computing, and a host of other areas. These exciting prospects are summarized in a new report from the National Science and Technology Council (NSTC), Advancing Quantum Information Science: National Challenges and Opportunities.

The NSTC report being issued today is the product of an interagency working group that was created to assess the current status of the field, coordinate activities across the relevant Federal agencies, engage stakeholders, and consider ways to address impediments and facilitate progress in quantum information science (QIS). Efforts to date have included internal discussions, agency-led and interagency workshops, and public requests for information; working group efforts will continue to include both Federal activity and outreach to the relevant research, development, and related communities in support of the broad ecosystem needed to realize the promise of quantum information science.

As a complement to the interagency report, the Department of Energy (DOE) is also publishing today the report of a recent roundtable on Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science, and Computing. The roundtable report provides a perspective from experts in the research community on promising scientific directions, needs for additional progress, and potential approaches consistent with the DOE mission. Other agencies have also held workshops and undertaken other activities reflecting the growing attention to QIS, including the recent launch of a cross-cutting National Science Foundation “metaprogram” on Connections in Quantum Information Science that complements and coordinates several existing programs within specific disciplines.

In addition to having strong connections to other related science and technology initiatives, there is significant synergy between the QIS effort and the National Strategic Computing Initiative (NSCI). The NSCI is a whole-of-Nation effort, created by Executive Order on July 29, 2015, to ensure continued U.S. leadership in high-performance computing (HPC) and to maximize the benefits of HPC for the economy and scientific discovery.

One key NSCI strategic objective is to establish, over the next 15 years, a viable path forward for future HPC systems. The NSCI pursues this objective through two concurrent paths: technologies that accelerate traditional digital computing after the limits of current semiconductor technologies are reached; and a range of new computing paradigms—including quantum computing—to address problems beyond the scope of traditional high performance computing. Some promising options on both NSCI paths depend on QIS. Understanding and controlling quantum effects will be critical to further miniatur-ization of charge-based complementary metal oxide semiconductor (CMOS) devices, and to refining alternatives for digital computing such as spin-based CMOS or superconducting computing. Basic and applied QIS research and development is also needed to clarify the range of computational problems a potential quantum computer could address, and to resolve the many challenges to fielding a practical quantum computer.

Today, OSTP is also publishing the National Strategic Computing Initiative (NSCI) Strategic Plan, authored by the NSCI Executive Council. Realizing the vision of the NSCI will demand a fully developed HPC ecosystem that meets the needs of government, industry, and academia. This Strategic Plan (Plan) focuses on areas where government engagement is essential in creating the technological capability, computational foundations, and workforce capacity to realize the vision of the NSCI. The Plan identifies the roles assigned to Federal agencies, and highlights ongoing and prospective activities that will contribute to NSCI’s goals. A combination of broad commercial drivers and government action is necessary to achieve the vision of the NSCI, but the success of the initiative depends upon deeper collaboration among the Federal Government, industry, and academia in the development, commercialization, and deployment of new HPC technologies and infrastructure. The NSCI strives to establish and support a collaborative ecosystem in strategic computing that will support scientific discovery and economic drivers for the 21st century, and that will not naturally evolve from current commercial activity.

OSTP intends to engage academia, industry, and government in the upcoming months to discuss activity in both fields, exchange views on key needs and opportunities, and consider how to maintain vibrant and robust national ecosystems for QIS research and development and for high-performance computing. These conversations will offer an opportunity to discuss mechanisms for addressing challenges in these rapidly-developing fields, including disciplinary and institutional boundaries, education and workforce training, and technology and knowledge transfer.

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Source: https://obamawhitehouse.archives.gov/blog/2016/07/26/realizing-potential-quantum-information-science-and-advancing-high-performance

Quantum Communications

Quantum information science combines two of the great scientific and technological revolutions of the 20th century: quantum mechanics on the one hand, and computer-based information science on the other. One of the fundamentally important research areas involved in quantum information science is quantum communications, which deals with the exchange of information encoded in quantum states of matter or quantum bits (known as qubits) between both nearby and distant quantum systems.

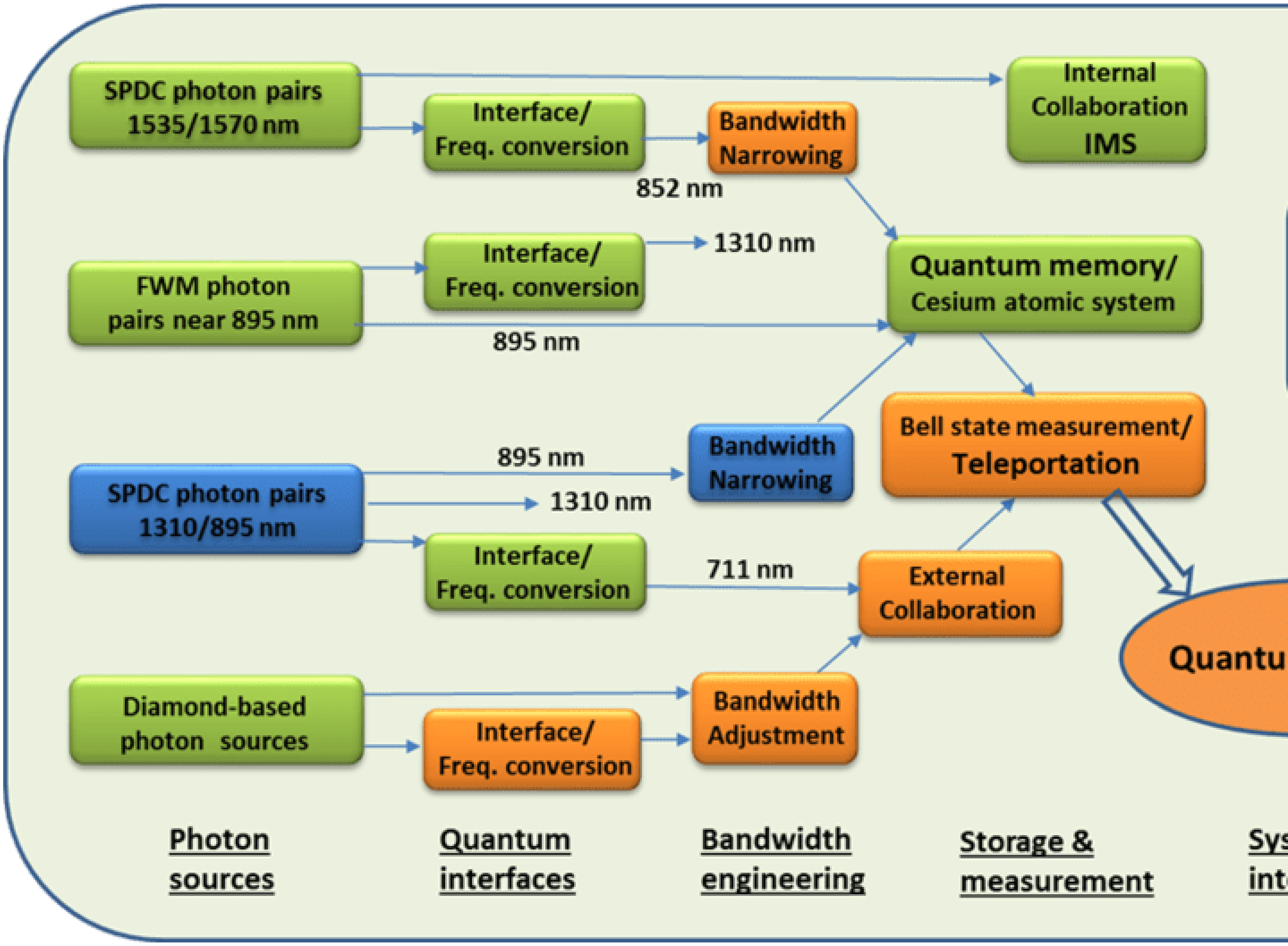
In July 2016, the National Science and Technology Council of the Executive Office of the President, in a report titled "Advancing Quantum Information Science: National Challenges and Opportunities", described Quantum Information Science (QIS) is "a foundational science," with "currently envisioned applications (that) include sensing and metrology, communications, simulation, and high-performance computing". The report also pointed out specifically that "Quantum communication, the ability to transmit information encoded in quantum states of light or matter, … is currently an active area of development". The report also states that "In the longer term, quantum networks will connect distributed quantum sensors… to allow long-distance transmission of quantum information". It further stated that solutions "could, with consistent attention and support, appear within 5 to 10 years."

In support of this initiative, the Quantum Communication Project in ITL performs fundamental research on the creation, transmission, interfacing, storage, processing and measurement of optical qubits – the quantum states of photons. Particular attention is paid to applying this research to future quantum information technologies.

Our accomplishments include

- high-speed quantum key distribution (QKD) systems for secure communications;
- narrow linewidth single photon sources for atomic interfacing;
- single-photon frequency conversion technologies to interface stationary qubits in the visible band with flying qubits in the telecommunication bands;
- efficient single photon detectors and ultra-high sensitivity spectrometers for the telecom wavelengths based on up-conversion technologies.

Our current research program is focused on the development and implementation of quantum repeaters. A quantum repeater enables quantum information exchange between two distant quantum systems. Quantum repeaters can be used to extend the operating distance for secure communications as well as to form future quantum networks. Our ongoing research aims to develop and implement and characterize the essential building blocks for quantum repeaters including single photon pair sources, quantum memories and quantum interfaces that can be practical and scalable when integrated into a quantum communication system. The figure shows our project roadmap.



The figure shows our project roadmap.

In summary, we perform research and development (R&D) on quantum repeaters and supporting measurement technologies. Our mission is to bridge the gap between fundamental quantum research and practical applications in industries and commercialization. Our R&D is aimed to promote US innovation, industrial competitiveness and enhance the nation's security. For more information, contact project leader Dr. Xiao Tang. For more information concerning the ITL Quantum Information program, please select link 'ITL Quantum Information Program'.

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