

ADVANCING QUANTUM INFORMATION SCIENCE: NATIONAL CHALLENGES AND OPPORTUNITIES

A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences



July 2016

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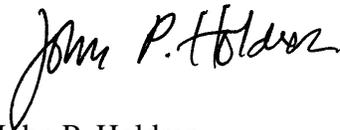
Dear Colleagues:

I am pleased to provide to you this report on *Advancing Quantum Information Science: National Challenges and Opportunities*. Recent advances in quantum information science (QIS) have increased interest and motivated new activity both domestically and internationally, making this report particularly timely. The document has been produced by an Interagency Working Group (IWG) on Quantum Information Science under the Subcommittee on Physical Sciences (PSSC) of the National Science and Technology Council. The report represents a coordinated effort across the numerous agencies and Executive Office of the President components participating in the IWG on QIS, and was informed by interactions with industry, academia, and other stakeholders. It is presented as a joint report of the PSSC's parent group, the Committee on Science, and of the parallel Committee on Homeland and National Security.

Quantum information science offers tremendous promise for both qualitative and quantitative leaps forward in information acquisition, processing, and transmission by exploiting quantum-mechanical phenomena. The field has seen rapid progress and growing attention in recent years, with ramifications across a broad range of fundamental sciences and for both near-term and long-term applications. Industry and international commitments signal the early stages of QIS-enabled devices and capabilities entering the marketplace, and are suggestive of much larger impacts to come.

Federal agencies in the United States have supported research and development in QIS consistent with agency missions for many years, and additional activities are planned or have recently been initiated. This report outlines a cohesive Federal approach going forward with an emphasis on broad and stable core programs, strategic and opportunistic targeted investments, and close monitoring and evaluation of Federal activity and of the field as a whole. Cooperation across government, academia, and the private sector will be of great value in enhancing the effectiveness of these efforts. The report highlights the identification of QIS as a priority for Federal coordination and investment as an important component of U.S. scientific leadership, national security, and economic competitiveness.

Sincerely,



John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

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The National Science and Technology Council (NSTC) is the principal means by which the Executive Branch coordinates science and technology policy across the diverse entities that make up the Federal research and development (R&D) enterprise. One of the NSTC's primary objectives is establishing clear national goals for Federal science and technology investments. The NSTC prepares R&D packages aimed at accomplishing multiple national goals. The NSTC's work is organized under five committees: Environment, Natural Resources, and Sustainability; Homeland and National Security; Science, Technology, Engineering, and Mathematics (STEM) Education; Science; and Technology. Each of these committees oversees subcommittees and working groups that are focused on different aspects of science and technology. More information is available at www.whitehouse.gov/ostp/nstc.

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About the Interagency Working Group on Quantum Information Science

The Interagency Working Group on Quantum Information Science (QIS) was created under the Subcommittee on Physical Sciences of the NSTC Committee on Science in order to assess Federal programs in QIS, monitor the state of the field, provide a forum for interagency coordination and collaboration, and engage in strategic planning of Federal QIS activities and investments.

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Report prepared by

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Executive Summary

Quantum information science (QIS) builds on uniquely quantum phenomena such as superposition, entanglement, and squeezing to obtain and process information in ways that cannot be achieved based on classical behavior. It is thus a foundational science. Its currently envisioned applications include sensing and metrology, communications, simulation, and high-performance computing, and it has the potential to enable significant scientific advances in physics, chemistry, biology, and materials science, among other domains. This report provides a brief description of the field, summarizes developments and potential impacts in various fields of technology and realms of basic research, identifies impediments to progress and potential approaches to addressing them, surveys Federal investments, and discusses the Federal path forward in the context of international and private-sector activity.

While recent progress in QIS has been substantial, a number of challenges remain. These include stability and continuity of funding, institutional and disciplinary boundaries, education and workforce training needs, knowledge transfer and interfaces with industry, and materials and fabrication. Federal activity includes long-standing and continuing programs at some agencies as well as newer efforts that are in the process of being implemented or are proposed. Federal efforts will provide new capabilities and will complement the activity and attention in academia and the private sector to begin addressing the identified impediments to progress.

Rapid technical advances and growing international interest and investments in quantum-enabled science and technology have marked the past few years. The interdisciplinary nature of the field, the reliance on complex, sophisticated, and precise physical arrangements in order to observe and utilize quantum behavior, and the potential for substantial economic consequences merit special attention. A coherent, all-of-government approach will facilitate advancement of QIS. This approach includes stable and sustained core programs, focused strategic investments in targets of opportunity, and continued close monitoring and evaluation of the field and of Federal and non-Federal activity. This report recommends that quantum information science be considered a priority for Federal coordination and investment, with particular attention to finding and implementing mechanisms to address identified impediments to the field.

Introduction

In 1994, Peter Shor, a computer scientist at AT&T Labs, made a landmark discovery that transformed the nascent field of Quantum Information Science (QIS). Shor's breakthrough (Shor 1994) was an efficient algorithm for factoring large numbers using a quantum computer—a computer that exploits quantum mechanical phenomena to perform calculations that can greatly exceed the capabilities of conventional digital electronics. The first logic operations performed on qubits—the quantum analog to the digital bits used to store information in today's computers—were demonstrated in the laboratory shortly thereafter (Monroe 1995). Subsequent developments in a variety of scientific and technological fields have similarly opened up new vistas in sensing, metrology, communication, and simulation.

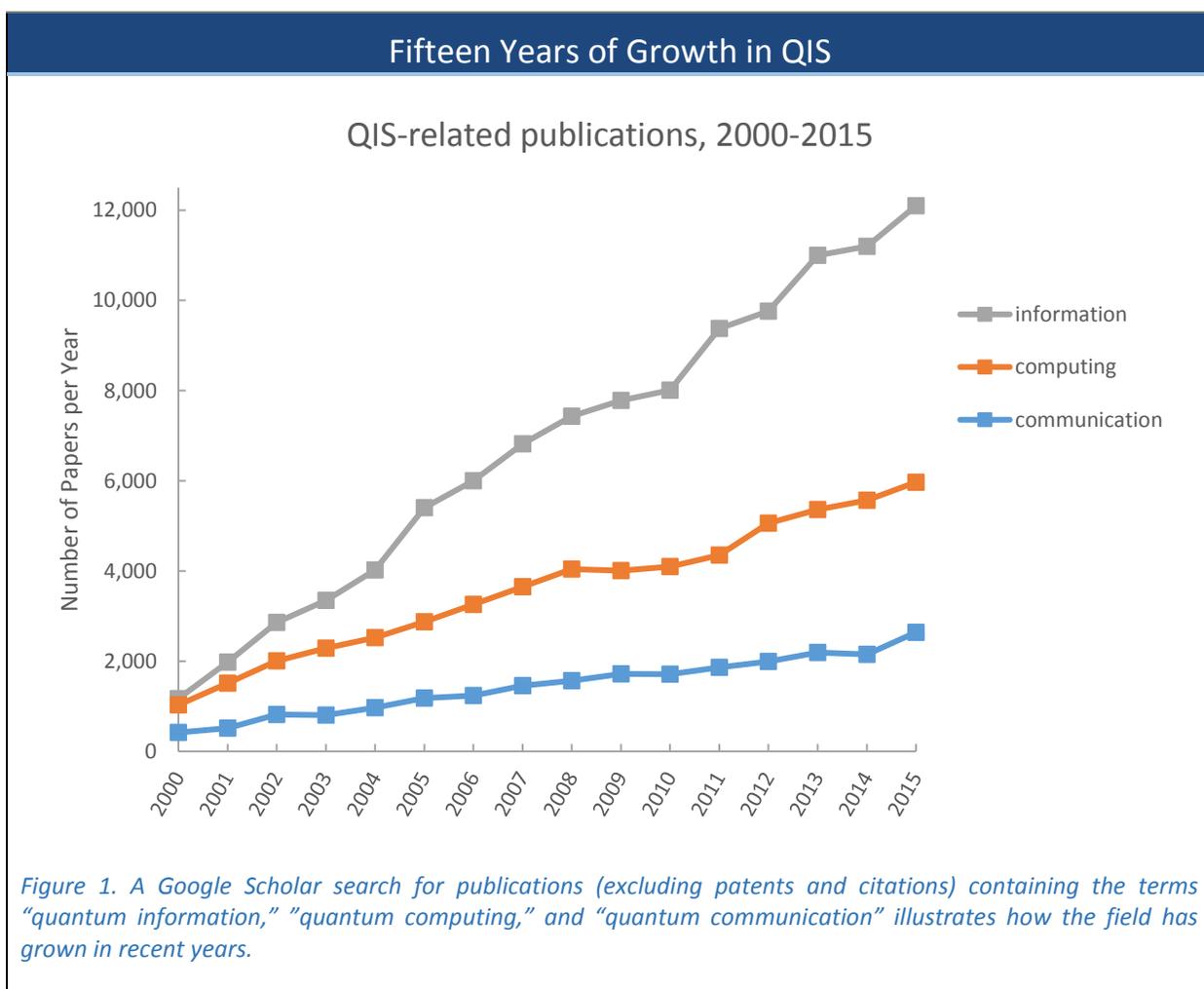
At the time of Shor's discovery, scientists had long been aware that quantum mechanics describes nature in a manner that transcends conventional logic and runs counter to intuition, but the technological possibilities were not easy to foresee. While it might not have been surprising that "classical" digital logic has limitations, it *did* come as a surprise that rewriting the rules of digital logic to include inherently quantum mechanical phenomena would allow computations far beyond those previously imagined. It is now understood that these counterintuitive quantum phenomena can be harnessed to build more powerful computers, manufacture more accurate sensors and detectors, make laboratory measurements with greater precision, and realize practical technologies relevant to both commerce and defense. QIS is far more than a new approach to computing or a collection of technological applications: it is a scientific paradigm in its own right.

QIS arises from the synthesis of two of the most powerful intellectual constructs of the 20th century: quantum theory and information theory. Quantum theory is a probabilistic description of energy and matter that accurately accounts for physical phenomena that are not well-explained by purely deterministic descriptions. Such quantum phenomena include the photoelectric effect, for which Einstein won the Nobel Prize in 1921, and the selective absorption of light by atoms that forms the basis for today's atomic clocks. Information theory characterizes information in terms of entropy, which forms the basis of modern digital communication through substantially more efficient encoding, error correction, and use of transmission capacity than prior techniques. Individually, these theories profoundly transformed civilization by enabling the development of technologies such as lasers and microelectronics that permeate modern life and by fundamentally changing the way modern society thinks about physics and information. Their synthesis in QIS has similar potential to produce revolutionary new technologies and further transform understanding of the world.

Why is QIS Different?

Current and future QIS applications differ from earlier applications of quantum mechanics such as the laser by exploiting the quantum properties of *superposition*, *entanglement*, and *squeezing* to acquire, process, and transmit information in ways that greatly exceed existing capabilities. Quantum systems, including single particles, are described by a set of variables that can take on a prescribed range of values. Until the value of each variable is measured, the system is in a *superposition* state that includes all possible measurement outcomes with some probability. An *entangled* state is a superposition of the states of multiple particles in which the properties of each particle are correlated with the properties of the other particles, even if the particles are separated by a large distance. *Squeezing* is a method of manipulating noise in quantum systems that obey the Heisenberg uncertainty principle. The uncertainty principle places a lower limit on the combined uncertainty in two related variables, but does not specify how the uncertainty is distributed between them. A *squeezed* state has the minimum allowed total uncertainty, but allows much more precise determination of one variable relative to the other.

QIS is currently at an inflection point, creating opportunities and challenges for the Nation. One measure, simplistic but telling, is the steady—and steep—increase in publications related to quantum communication, computing, and information; a plot of these publications over the past 15 years is shown in Figure 1. The pace of basic and applied research as well as development and demonstration is increasing and is likely to continue to accelerate in the near-term future. At the same time, advancing the field still requires deep scientific expertise and technical specialization that are not easily transferred to the U.S. high-tech economy. The QIS research community, dominated by academics and a handful of research groups in government and industry, will be hard pressed to meet these demands. Furthermore, a global race is developing. National governments and private companies are stepping up their investments in recognition of the potential implications of a QIS-based technological revolution. Numerous workshops over more than a decade, sponsored by Federal agencies or organizations supported by Federal agencies, have drawn increasing attention to the value and importance of QIS. A continued robust research and development ecosystem for QIS in the United States is necessary so that the U.S. research community, industry, and government agencies are engaged and poised to take advantage of technological breakthroughs when they occur. Strengthening this ecosystem will enhance U.S. national security, bolster U.S. economic competitiveness, and extend U.S. leadership in scientific discovery.



QIS and Technology

QIS is expected to open entirely new vistas of technological development. The greatest impacts are likely to be felt first in sensing and metrology, next in communication and simulation, and finally in computing.

Sensing and Metrology

QIS is already pushing the boundaries of sensing and metrology. The atom interferometers that are useful for inertial navigation, described in the accompanying box, can also be adapted for use as gravimeters, with applications ranging from Earth system monitoring to pinpointing the location of subterranean mineral deposits. Magnetometers based on point defects in diamond can operate in close proximity to the human body and also in extreme environments relevant to military and industrial applications. QIS-based timekeeping devices such as the quantum logic clock (Chou 2010) at the National Institute of Standards and Technology (NIST) are among the most precise in the world. Photon sources and single photon detection techniques being developed for longer-term applications such as quantum communication will, in the near term, improve the calibration of light-sensitive detectors (Levine 2015) and enable detection of trace elements in low-absorption and quantity-limited samples. With continued investment and effective coordination between the research community and industry, a broad range of QIS-enhanced sensors could be available in the U.S. marketplace within 5 years, with still more under development.

QIS for Navigation

The GPS networks that many ships and aircraft depend on for precise navigation can be jammed or physically attacked. In the absence of GPS, these vessels rely on inertial navigation systems that measure acceleration and rotation. Cold atoms traveling in opposite directions around a loop form wavelike interference patterns that are exquisitely sensitive to rotation. By replacing the less-accurate gyroscopes currently used to measure rotation with QIS-based atomic sensors (e.g., Durfee 2006), it will be possible to navigate accurately without GPS for at least 100 times longer.

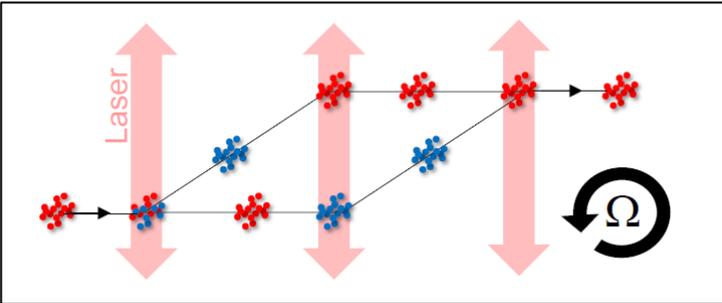


Figure 2. In the above schematic of an atomic rotation sensor, lasers are used to place atoms in a superposition state and send them in opposite directions around a loop. If the sensor is rotating about an axis perpendicular to the loop, the atoms on each path will interfere with one another when the cloud recombines. (Credit: Willis/ONR)

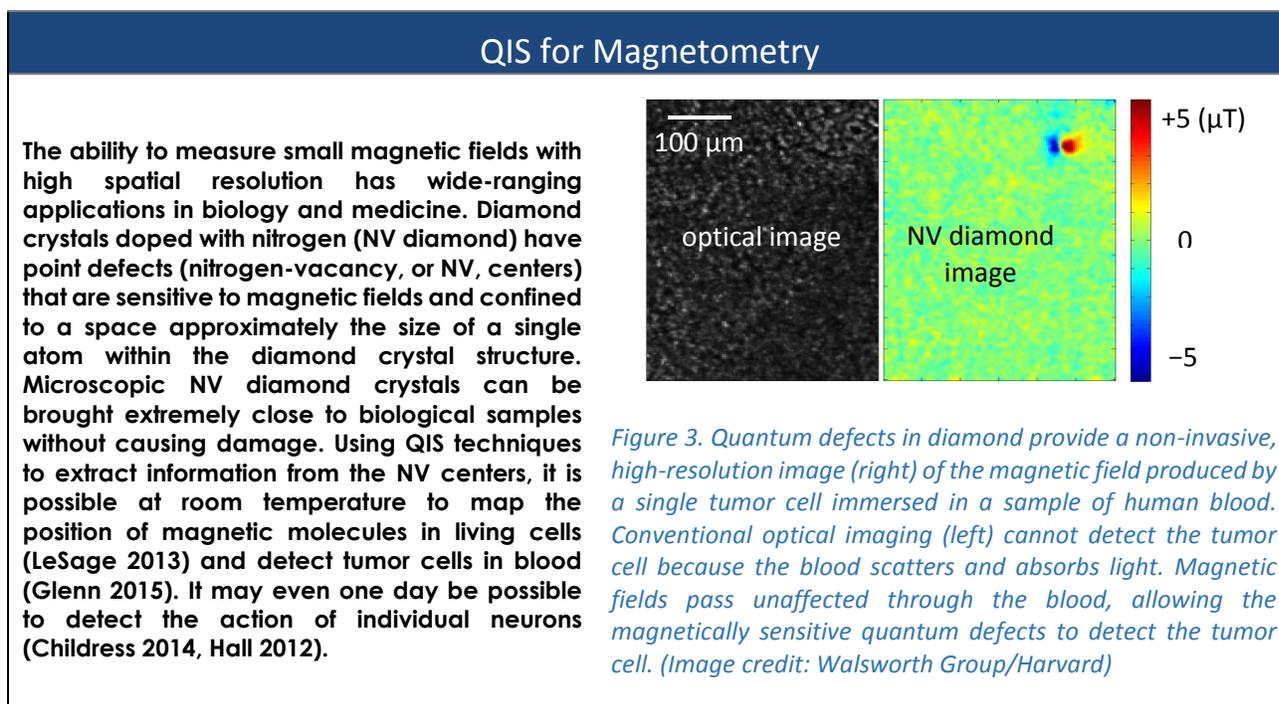
Communication

Quantum communication, the ability to transmit information encoded in quantum states of light or matter, is a challenging technical problem because the information stored in quantum states is irrevocably altered when the quantum system is disturbed. This has the advantage that eavesdroppers are easily detected, leading to quantum-secure methods of communication, and the disadvantage that signals cannot be replicated or amplified. Quantum-secure communication is currently an active area of development. Quantum key distribution, a secure method for generating an encryption key between distributed partners which may have useful applications in networks, has received recent industry attention in both the United States and abroad. Other applications that may see near-term

implementation, including unforgeable virtual money and quantum fingerprinting techniques to determine whether two remote pieces of data (such as financial records) are identical, demonstrate the potential for quantum communication to affect commerce. In the longer term, quantum networks will connect distributed quantum sensors, for example for global seismic monitoring, and allow quantum information to flow coherently between the internal components of the quantum simulators and computational devices discussed below. Solutions that build on current experimental work to develop reliable photon sources and technology to allow long-distance transmission of quantum information as well as ongoing theoretical work on protocols for sharing data, for example between quantum processors, could, with consistent attention and support, appear within 5 to 10 years.

Simulation

Quantum simulators use readily-manipulated quantum systems to investigate the properties of other quantum systems that are difficult to study directly, such as complex materials. Materials calculations are the second-largest use of the Department of Energy's (DOE's) National Energy Research Scientific Computing Center (NERSC), one of the primary supercomputing facilities available to the U.S. research community. Quantum simulators have the potential to produce efficient solutions to these problems and others in computational science that are limited by the inherent capabilities of traditional high performance computers. Prototype quantum simulators based on several different technologies have already been demonstrated in the laboratory: magnetic materials have been simulated using arrays of trapped ions (Monroe 2015) and the dynamics of simple chemical reactions have been simulated using both cold atoms (Torrontegui 2012) and quantum dots (Smirnov 2007). In the long term, quantum simulation may allow us to understand the properties of extraordinary materials such as high-temperature superconductors, predict interactions of complex molecules, and allow models of nuclear and particle physics to be explored in previously inaccessible regimes. Quantum simulation has not yet tackled problems that are intractable with conventional computers; however, there appears to be an opportunity to implement selected applications that would otherwise not be achievable in areas such as chemistry, materials science, and physics within a decade.



Computing

Quantum computers process information stored in qubits, which are each individually in superposition states and are entangled with one another. The unique quantum properties of the qubits allow a quantum computer to perform certain computations much faster, in some cases exponentially faster, than is possible using conventional computers. The most striking example is Shor's algorithm for integer factorization, discussed above, which demonstrates the power of quantum computers to solve problems of practical significance. Exponential quantum speedups have been discovered for problems in chemistry and materials science (Brown 2010, Hastings 2015), and particle physics (Jordan 2012); quantum computation may eventually revolutionize these and other scientific fields. Quantum algorithms offering more modest speedups have been discovered for searching and related tasks (Grover 1996, Reichart 2012), whose applications are ubiquitous. More speculative research has raised the possibility of quantum speedups for a wide variety of problems related to optimization and scientific computing, such as machine learning, software verification and validation, and radar scattering calculations (Aaronson 2015, Clader 2013, Pudenz 2012). Quantum computing hardware is currently at the laboratory prototype stage and is progressing steadily; one commercial entity has made a 5-qubit processor available to the research community over the internet. While further substantial scale-up will be needed to test algorithms such as Shor's, systems with tens of entangled qubits that may be of interest for early-stage research in quantum computer science will likely be available within 5 years. Developing a universal quantum computer is a long-term challenge that will build on technology developed for quantum simulation and communication. Deriving the full benefit from quantum computers will also require continued work on algorithms, programming languages, and compilers. The ultimate capabilities and limitations of quantum computers are not fully understood, and remain an active area of research.

Ion Traps as Tools for QIS

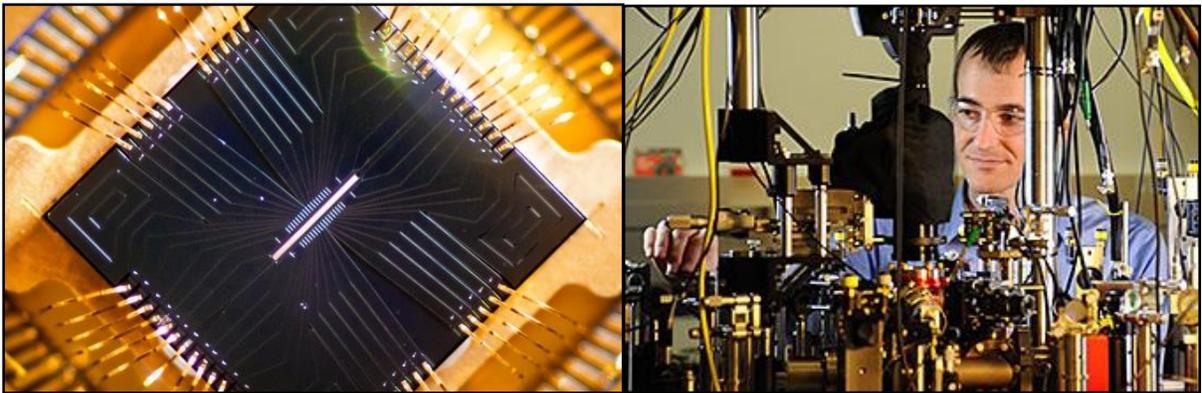


Figure 4. Trapped ions are one of several promising technologies for QIS applications. The chip shown on the left, manufactured by Sandia National Laboratories, can trap a string of ions just above the chip's surface. Quantum information can be stored and processed by manipulating the ions with lasers and microwave radiation. Similar chips could one day form the backbone of a quantum computer. The NIST Quantum Logic Clock, shown on the right, is a laboratory-scale experiment that uses an entangled helper ion to increase the accuracy and stability of an atomic clock based on a trapped aluminum ion. Superconducting circuits, quantum defects in materials, quantum dots, and topological materials also hold promise for QIS applications. (Photo credit: JQI, Burrus/NIST)

QIS and Fundamental Science

Even as technical applications are developed and commercialized, QIS remains a rich area of scientific inquiry, simultaneously providing greater insight into the natural world and the nature of information itself. In recent years, quantum information science has seen increasingly widespread use in other areas of science, both experimental and theoretical. High-precision measurements enabled by control of quantum systems such as individual atoms, molecules, and NV centers have been used in biology to probe the interiors of cells (Kucsko 2013) and in physics to test fundamental symmetries (ACME 2014) and search for dark matter (van Bibber 2013). The tensor networks developed to compactly express quantum states by exploiting their entanglement structure have yielded powerful new computational methods for simulating materials (Sachdev 2009) and have led to progress on longstanding problems in theoretical condensed matter physics such as the classification of phases of matter. Quantum information concepts such as entanglement, error correction, and circuit complexity have been applied to central problems of quantum gravity such as understanding the emergence of spacetime (Pastawski 2015) and the interiors of black holes (Harlow 2013). Mathematical techniques from quantum information have also increasingly been used to solve problems in many areas of classical computer science, including algorithms, cryptography, and the design of error-correcting codes (Drucker 2011). There are also hints that QIS concepts may be relevant to seemingly more distant physical systems such as photosynthesis, phonon-mediated receptors in the nose and brain, and the navigation systems of migratory birds (Lambert 2012).

Bell Tests: From Philosophy to Quality Assurance

Entanglement was at the heart of a philosophical conundrum as quantum theory was initially developed: how can it be true that the properties of two entangled particles are correlated if the particles' properties are indeterminate and can only be specified as probabilities until a measurement is made on one or both of them? In 1935, Einstein, Podolsky, and Rosen postulated that it could be possible to describe the properties of entangled particles with "hidden variables" that would only be accessible to an observer by making a measurement (Einstein 1935). In 1964, John Bell showed that it is possible to determine experimentally whether hidden variables exist or whether the properties of entangled particles are truly undetermined until a measurement is performed (Bell 1964). Within the last year, three loophole-free "Bell test" experiments have definitively ruled out hidden variables (Giustina 2015, Hensen 2015, Shalm 2015). Bell tests have implications for QIS applications well beyond philosophy. For example, Bell tests form the basis for device-independent secure cryptographic protocols such as the production and distribution of cryptographic keys (Pironio 2010). And, because Bell tests directly measure entanglement, they serve as a verification tool for laboratory hardware and engineered devices.



Figure 5. Physicist Krister Shalm with the photon source used in NIST's 2015 Bell test that strongly supports the existence of quantum entanglement. (Photo Credit: Burrus/NIST)

Addressing Impediments to Progress

As the Interagency Working Group surveyed the state of the field, it became apparent that despite the considerable advances in recent years, there is great potential for enhancing the rate of progress in QIS by addressing the issues described below. Federal agencies are already working to address these impediments, and plan to implement solutions as their QIS programs evolve and grow. A cooperative effort between government, academia, and the private sector to find and implement solutions will be even more effective than Federal efforts alone in overcoming impediments and reaping the benefits QIS has to offer.

Institutional Boundaries

Much of the research in QIS has been conducted within existing institutional boundaries. For example, individual Divisions of the National Science Foundation (NSF) have funded QIS-related research in individual university departments. The next critical steps in QIS R&D will require increased collaboration across these boundaries. Teams with a diverse range of skills will be needed in order to, for example, translate a proof-of-principle source of entangled photons on an optical table in a physics laboratory to a robust, scalable platform that can be incorporated into a real-life quantum network. Federal programs that fund diverse teams, such as those described in the following section of this report, have already proven to be effective in accelerating the pace of QIS research. Similarly, university-based centers and institutes that facilitate faculty collaboration across departmental boundaries have been remarkably productive. Several universities that can be considered leaders in QIS have taken the initiative to form their own centers and institutes. Others have partnered with private foundations or the government. Continued efforts to surmount barriers within institutions and encourage research collaborations that bring together diverse skills and expertise are likely to translate directly into accelerated progress in QIS.

Education and Workforce Training

Both academic scientists and industry representatives identify discipline-specific education as insufficient for continued progress in QIS. At this stage in the field's evolution, a deep understanding of quantum mechanics is required to move forward with both basic research and technical applications. Quantum mechanics is rarely taught in depth outside of physics departments, which could explain why the physics community has embraced QIS to a greater degree than, for example, computer scientists or applied mathematicians. However, QIS is not purely physics. Computer science and applied mathematics are essential to many of the areas outlined above. Electrical engineering and systems engineering are also critical, and process engineering will become more important as QIS technology is deployed on a larger scale. In general, QIS R&D requires and will continue to require a diverse range of skills and expertise that varies from one application to another. Some universities, led by the efforts of forward-thinking researchers, are already designing undergraduate and introductory graduate level courses for students in engineering and other disciplines outside of physics that incorporate QIS topics. The university-based QIS centers mentioned above also provide students with the opportunity to develop a skill set suited to QIS R&D. As QIS progresses and grows, lessons learned from these early efforts to support QIS education and workforce training can be applied to meet future needs.

Technology and Knowledge Transfer

As QIS applications mature from laboratory prototypes into potentially marketable technology, knowledge must be transferred from universities and national laboratories to an appropriately skilled private-sector workforce. Industry representatives have identified existing Federal programs such as the Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) grants and NSF's

Grants Opportunity for Academic Liaison with Industry (GOALI) program as valuable, but these programs do not address many of the challenges industry faces in bringing QIS applications to market. One of the key challenges is the lack of a consistent framework to support R&D that develops a laboratory prototype into a final marketable product. Another challenge involves licensing of intellectual property (IP) from universities; much of this IP is pre-competitive because QIS is not yet a mature field, but is being valued similarly to developed, more marketable technologies. A third is connecting capable and qualified graduates with companies in need of their specialized skills. Small companies, in particular, often lack the resources to recruit widely or support interns. These challenges are common to many areas of research and development, but are particularly acute in emerging and rapidly-developing fields such as QIS. The Federal government has been actively focused on improving technology transfer¹ and strengthening the STEM workforce.² At the same time, universities can take the initiative to prepare students for the full range of possible career options and facilitate translating the world-class research performed on campus into high-impact technology that will benefit society.

Materials and Fabrication

Much of the effort to develop practical QIS applications depends on the availability of materials with the appropriate quantum properties and the ability to package hardware that may currently fill several large laboratory tables into a functionally equivalent form that can be manufactured and built into usable devices. Progress in certain areas of QIS is already limited by the availability of fabrication capabilities for quantum materials, including the NV diamond crystals mentioned above. Design, integration, and fabrication of new devices for QIS applications are engineering challenges that will require capabilities beyond those readily available. Providing the research community with greater access to Federal facilities that allow exploration of new materials and device concepts will enhance progress in basic and applied QIS research. Development and deployment of QIS applications will be contingent on reliable production of novel quantum materials. Fundamental improvements in fabrication tools and techniques will be required to produce these new materials and the QIS devices that incorporate them at scale. The manufacturing and systems-level engineering challenges associated with quantum device production are not yet fully understood but will become increasingly important as the field develops and demand for such devices increases.

Level and Stability of Funding

QIS has historically suffered from an overall instability of U.S. research funding that has negatively impacted both the pace of technical progress and development of a QIS workforce in the United States. Much of the instability can be traced to insufficient coordination among Federal agencies: as individual agency programs either grew or terminated, the overall level of Federal QIS research funding fluctuated greatly. Fluctuations in Federal and other U.S. funding led to discontinuities in university-based research programs and contributed to promising young as well as senior researchers choosing to pursue alternate careers or look for opportunities outside the United States. Coordinating Federal QIS programs to maintain a smooth funding profile with an overall level sufficient to support progress will enhance the value of these Federal investments and attract talent to the field. Coordination is one of the objectives of the current Interagency Working Group in QIS.

¹ <https://www.whitehouse.gov/the-press-office/2011/10/28/presidential-memorandum-accelerating-technology-transfer-and-commercial>

² https://www.whitehouse.gov/sites/default/files/microsites/ostp/stem_stratplan_2013.pdf

Government Investment in QIS

Federal agencies have supported research in QIS and related areas since the field emerged over 20 years ago. This support has played a significant part in enabling U.S. scientists to establish their present leading roles in the field. Federally-funded basic and applied research in QIS is currently on the order of \$200 million a year. The Department of Defense (DOD) services and Office of the Secretary of Defense, NIST, and NSF have provided basic research support for QIS, while the Defense Advanced Research Projects Agency (DARPA) and the Intelligence Advanced Research Projects Activity (IARPA) have funded a series of targeted, limited-term programs. In FY 2017, DOE plans to initiate activity and support new programs in QIS research relevant to the DOE mission. Agency programs are structured to take advantage of scientific and technical opportunities as well as to begin to address the impediments listed above.

DOD

DOD's basic research agencies in the individual services—the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), and the Office of Naval Research (ONR)—as well as the Office of the Secretary of Defense (OSD) actively support basic and applied research in QIS and related technology with a focus on national security applications such as precision navigation, precision timing, and secure quantum networks. OSD has made 12 Multidisciplinary University Research Initiative (MURI) awards for QIS-related topics from FY 2011 through FY 2015. These awards provide a higher level of support for a longer period of time than many other government-funded programs, and have been lauded by the research community as a support mechanism that is well-suited to complex, team-based QIS projects. Starting in FY 2016, OSD is supporting a Tri-Service Quantum Science and Engineering Program (QSEP) that will exploit expertise at the Joint Service laboratories to prototype a scalable quantum network, develop and entangle practical quantum memories, and demonstrate a high-sensitivity sensor application across the network. The Army, Air Force, and Naval Research Laboratories also support their own programs related to QIS. Notably, the Army Research Laboratory (ARL) began in FY 2015 a five-year collaborative basic research effort connecting ARL, academic, industrial, and other government researchers to develop a multi-site, multi-node, modular quantum network with the long-term objective of identifying and providing beyond-classical capabilities for DOD mission needs. The service agencies also support other efforts such as those of the Laboratory for Physical Sciences (LPS), which collaborates with ARO in the sponsorship and administration of numerous academic quantum computing research projects around the world. LPS is a unique facility at the University of Maryland where university and Federal government personnel collaborate on research in advanced communication and computer technologies, including quantum computing.

QIS and the NSCI

In addition to having strong connections to other related science and technology initiatives, including the National Nanotechnology Initiative and the Materials Genome Initiative, QIS will play a key role in the National Strategic Computing Initiative (NSCI). Established by Executive Order 13702 in 2015, the NSCI aims to sustain U.S. leadership in high performance computing (HPC). A 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 new computing paradigms to address problems beyond the scope of traditional high performance computing. Promising options on both paths depend heavily on QIS. Understanding and controlling quantum effects will be critical to further miniaturization 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 R&D 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.

The Defense Advanced Research Projects Agency (DARPA) has funded and continues to fund programs that target different areas in QIS. The Quantum Assisted Sensing and Readout (QuASAR) program seeks to develop sensors that operate near and below the standard quantum limit; the Quiness program is exploring a variety of approaches to improving quantum communications; the Optical Lattice Emulator (OLE) program aimed to simulate the properties of quantum materials in atomic systems; and the Quantum Entanglement Science and Technology (QuEST) program sought innovative approaches to overcome outstanding challenges in QIS. The recently launched Fundamental Limits of Photon Detection (Detect) program aims to develop innovative approaches enabling revolutionary advances in the modeling and fabrication of photon detectors which could have applications across the QIS field.

DOE

Over the past decade, individual DOE laboratories funded by the Office of Science and the National Nuclear Security Administration (NNSA) have taken the initiative to develop expertise in specific areas of QIS, recognizing the increasing relevance of the field to their work to support DOE's mission. Starting in FY 2017, DOE will support a core program of research to explore the applicability of quantum simulation and computing to scientific questions of interest to DOE. Initially, these efforts will focus on implementing testbeds for use by the research community to explore quantum computations, research in underpinning applied mathematics and computer science, and algorithm development for applications in Office of Science program areas, including Basic Energy Sciences and High Energy Physics. In addition, DOE is working with the scientific community to explore QIS-based approaches to improve quantum materials and structure synthesis, fabrication, characterization, and theory for technologies in physical science experiments conducted in DOE facilities. A workshop on Basic Research Needs in Quantum Materials for Energy Relevant Technology was conducted in February 2016; the report of this workshop is expected to be released in the summer of 2016.

IARPA

IARPA has recently funded and plans to continue funding programs that target specific advances in quantum computing over the next several years. The Logical Qubits Program³ seeks to overcome the limitations of current multi-qubit systems by building a logical qubit from a number of imperfect physical qubits and the Quantum Enhanced Optimization Program⁴ seeks to harness quantum effects required to enhance quantum annealing solutions to hard combinatorial optimization problems. IARPA has continued interest in funding research on new computational methods, including algorithms, based on quantum systems whose attributes are matched to an efficient or secure solution of intelligence problems.

NIST

NIST's work in QIS, which began over 20 years ago, grew to its present level through a series of initiatives extending back to 2005. NIST was the first to demonstrate a two-qubit gate (Monroe 1995), has developed some of the world's most sensitive single photon detectors (Marsili 2013), and has exploited entanglement to make a quantum logic clock (Chou 2010). The current NIST program focuses on metrology in support of quantum communications, quantum computation, and quantum-based measurements. In FY 2016, NIST is supplementing existing resources with new funds to support a thrust in Quantum Based Sensors and Measurements that directly supports Federal efforts in QIS. In FY 2017,

³ <http://www.iarpa.gov/index.php/research-programs/logiq>

⁴ <http://www.iarpa.gov/index.php/research-programs/qeo>

NIST plans to increase support for research in quantum computing as part of a larger effort to fulfill NIST's role in the National Strategic Computing Initiative. NIST also supports two joint centers in QIS research at the University of Maryland (UMD). The Joint Quantum Institute⁵ (JQI) was established in 2006 through a cooperative effort of NIST, UMD, and the Laboratory for Physical Sciences⁶ to serve as a world-class research institute through the interchange of ideas among atomic physics, condensed matter, and quantum information scientists. In 2014, the Joint Center for Quantum Information and Computer Science⁷ (QuICS) was established by NIST and UMD as a complement to JQI, with a focus on how quantum systems can be used to store, transmit, and process information and including strong participation from computer scientists. QuICS and JQI are colocated and interact strongly to train scientists for future industrial and academic opportunities in QIS in addition to performing cutting-edge research.

NSF

The NSF has funded decades of basic research in the physical sciences, mathematics, computer science, and engineering that supports the foundations of QIS. In addition, NSF's Physics Division has for over a decade had a program in "Quantum Information Science and Revolutionary Computing"⁸ specifically dedicated to QIS. NSF also funds two QIS-related Physics Frontier Centers. The Institute for Quantum Information and Matter at Caltech⁹ has been focused on quantum information, quantum matter, quantum optics, and quantum mechanical systems since 2011, and the Physics Frontier Center at the JQI¹⁰ has been exploring various means of controlling and processing quantum coherence and entanglement since 2008. The productivity¹¹ of both these centers and the JQI itself demonstrates how progress can be enhanced by bringing together diverse teams and allowing students and early-career researchers to pursue a path defined by research questions rather than institutional boundaries. In recent years, NSF has seen an increasing number of high-quality QIS proposals submitted across the Foundation. NSF has responded by creating new programs and adapting existing programs to better meet the needs of the QIS research community. In FY 2016, NSF's Engineering Directorate selected "Advancing Communication Quantum Information Research in Engineering"¹² as a new topic for its Emerging Frontiers in Research and Innovation program, which funds multidisciplinary teams at a higher level than a standard award to pursue paradigm-shifting research. QIS has been added to the list of suggested topical areas¹³ for NSF's SBIR/STTR program, and NSF's Physics Division selected QIS as one of two topics for a special FY 2016 program to promote a collaborative approach and provide workforce training at the postdoctoral level through Focused Research Hubs in Theoretical Physics.¹⁴ To further address the challenges associated with funding research that spans boundaries across Divisions and Directorates, NSF has just announced a new metaprogram to begin in FY 2017, "Connections in Quantum Information Science".¹⁵ The metaprogram will be organized by NSF's Directorates for Mathematical and Physical Sciences (MPS), Engineering (ENG),

⁵ <http://jqj.umd.edu/>

⁶ <http://www.lps.umd.edu/>

⁷ <http://quics.umd.edu/>

⁸ http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505207

⁹ <http://iqim.caltech.edu/>

¹⁰ <http://jqj.umd.edu/pfc>

¹¹ <http://iqim.caltech.edu/research/publications/>, <http://jqj.umd.edu/research/publications>

¹² http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13708

¹³ <http://www.nsf.gov/eng/iip/sbir/topics/IT.jsp>

¹⁴ <http://www.nsf.gov/pubs/2016/nsf16501/nsf16501.htm>

¹⁵ http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505283&org=DMR&from_org=NSF

and Computer and Information Science and Engineering (CISE) to foster QIS research at the intersection of these three disciplines.

The Broader Context

QIS is an increasingly international field. In just the last two years, several nations have announced new programs with significant QIS components that will supplement existing R&D investments. For example, the United Kingdom committed¹⁶ in 2014 to a five-year quantum technologies program that includes four new hubs in specific technological areas and announced¹⁷ in 2016 a related effort to train a skilled quantum technology workforce. In 2015, the Netherlands embarked upon a ten-year effort to accelerate the development of quantum computing at the Delft University of Technology's quantum technology institute. In addition, the European Commission has announced plans to launch a new ten-year flagship project in quantum technologies, beginning in 2018.¹⁸ With the increase in activity abroad, international collaboration is becoming more common and researchers are crossing borders to pursue the most exciting scientific questions.

The level of private sector investment in QIS is also increasing. Several large U.S. companies, as well as a number of startups, have new investments in QIS projects that include the development of quantum computers and the software required to use them. Some of these companies are providing support to academic research groups both in the United States and abroad. At the same time, a growing number of small companies are focused on bringing specific quantum devices, such as the navigation sensors described above, to market. Building and strengthening connections between the QIS research community and U.S. industry will be increasingly important as QIS applications mature and competition ramps up in the worldwide marketplace.

The Path Forward

The significant advances in QIS over the past 5 years are a direct result of the long history of Federal investment in this area. Recognizing the strategic importance of emerging QIS applications and the rich ground for scientific inquiry, Federal agencies are placing a higher priority on QIS than in the past, adapting existing programs to address identified impediments to progress and developing new programs to build upon and complement existing ones. Agencies are also exploring possibilities for bringing government, academia, and industry together to enhance knowledge transfer and establish a skilled future workforce in QIS. The current slate of agency activities forms a foundation for a coherent, all-of-government approach to QIS that includes:

- Stable and sustained core programs that can be enhanced as new opportunities appear and restructured as impediments evolve;
- Strategic investment in targeted, time-limited programs to achieve concrete, measureable objectives;
- Continued close monitoring of the field to evaluate the outcome of Federal QIS investments and quickly adapt programs to take advantage of technical breakthroughs as they are made.

¹⁶ <http://uknqt.epsrc.ac.uk>

¹⁷ <https://www.epsrc.ac.uk/newsevents/news/ministerdtptgt/>

¹⁸ [http://www.nature.com/news/europe-plans-giant-billion-euro-quantum-technologies-project-1.19796;](http://www.nature.com/news/europe-plans-giant-billion-euro-quantum-technologies-project-1.19796)
<http://www.sciencemag.org/news/2016/04/europe-bet-1-billion-quantum-technology>

These three principles offer a good approach to continued U.S. leadership in QIS, but in order to be effective they must be rigorously implemented and even expanded in order to maximize impact. Sustained core programs will allow established researchers to continue their work, give students confidence that QIS is a field with a future, and provide a solid base for translating laboratory demonstrations into marketable technology. Targeted, time-limited programs are an effective mechanism for achieving well-defined technical advances and allow quick adaptation to a changing technological landscape. Continued monitoring is required to ensure that the Federal strategy for QIS investment remains effective into the future and to avoid technological surprise. Carefully controlled growth of funding and programs, coupled with close monitoring of progress and readiness to apply greater focus and resources as events warrant, should allow the United States to address the impediments to progress and remain at the forefront of this rapidly advancing, strategically important field. QIS should be considered a priority for Federal coordination and investment, with particular attention to finding and implementing mechanisms to address the identified impediments to progress and a commitment to keep the United States at the leading edge of scientific and technological developments.

References

- Aaronson, S. "Read the fine print." *Nature Physics* 11 (2015) pp. 291-293
- The ACME Collaboration, "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron." *Science* 343 (2014) pp. 269-272
- J. Bell. "On the Einstein-Podolsky-Rosen Paradox." *Physics* 1 (1964) pp. 195-200
- Brown, K. Munro, W., and V. Kendon. "Using quantum computers for quantum simulation." *Entropy* 12 (2010), pp. 2268-2307
- Childress, L., Walsworth, R., and M. Lukin. "Atom-like crystal defects: From quantum computers to biological sensors." *Physics Today* 67 (2014) pp. 38-43
- Chou, C.W., *et al.* "Frequency Comparison of Two High-Accuracy Al⁺ Optical Clocks." *Physical Review Letters* 104 (2010): 070802
- Clader, B.D., Jacobs, B.C., and C.R. Sprouse. "Preconditioned quantum linear systems algorithm." *Physical Review Letters* 110 (2013) 250504
- Drucker, A. and R. de Wolf. *Theory of Computing Library Graduate Surveys* 2 (2011) p. 1
- Durfee, D.S., Shaham, Y.K., and M.A. Kasevich. "Long-Term Stability of an Area-Reversible Atom-Interferometer Sagnac Gyroscope." *Physical Review Letters* 97 (2006) 240801
- Einstein, E., Podolsky, B., and N. Rosen. "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* 47 (1935) pp. 777-780
- Giustina, M., *et al.* "Significant Loophole-Free Test of Bell's Theorem with Entangled Photons." *Physical Review Letters* 115 (2015) 250401
- Glenn, D.R., *et al.* "Single-cell magnetic imaging using a quantum diamond microscope." *Nature Methods* 12 (2015), pp. 736-738
- Grover, L. "A fast quantum mechanical algorithm for evaluating formulas." *Proceedings of STOC* (1996) pp. 212-219
- Hall, L.T., *et al.*, "High spatial and temporal resolution wide-field imaging of neuron activity using quantum NV-diamond." *Scientific Reports* 2 (2012) DOI: 10.1038
- Harlow, D. and P. Hayden. "Quantum computation vs. firewalls" *Journal of High Energy Physics* 6 (2013) pp. 85-151
- Hastings, M., *et al.* "Improving algorithms for quantum chemistry." *Quantum Information and Computation* 15 (2015), pp. 1-21
- Hensen, B., *et al.* "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres." *Nature* 526 (2015) pp. 682-686
- Jordan, S., Lee, K., and J. Preskill. "Quantum algorithms for quantum field theories." *Science* 335 (2012) pp. 1130-1133
- Kucsko, G., *et al.* "Nanometre-scale thermometry in a living cell." *Nature* 500 (2013) pp.54-58
- Lambert, N. *et al.* "Quantum biology." *Nature Physics* 9 (2013) pp. 10-18
- LeSage, D., *et al.* "Optical magnetic imaging of living cells." *Nature* 496 (2013) pp. 486-489

- Levine, Z. *et al.* "Absolute calibration of a variable attenuator using few-photon pulses." *Optics Express* 23 (2015) pp. 16372-16382
- Marsili, F., *et al.* "Detecting single infrared photons with 93% system efficiency." *Nature Photonics* 7 (2013) pp. 210-214
- Monroe, C., *et al.* "Demonstration of a Fundamental Quantum Logic Gate." *Physical Review Letters* 75 (1995) pp. 4714-4717
- Monroe, C., *et al.* "Quantum Simulation of Spin Models with Trapped Ions." *Proceedings of the International School of Physics 'Enrico Fermi' Course 189* (2015) pp. 169-187
- Pastawski, F., *et al.* "Holographic quantum error-correcting codes: toy models for the bulk/boundary correspondence." *Journal of High Energy Physics* 6 (2015) pp. 149-194
- Pironio, S., *et al.* "Random numbers certified by Bell's theorem." *Nature* 464 (2010) pp. 1021-1024
- Pudenz, K. and D. Lidar. "Quantum adiabatic machine learning." *Quantum Information Processing* 12 (2012) pp. 2027-2070
- Sachdev, S. "Tensor networks: a new tool for old problems" *Physics* 2 (2009) p. 90
- Shalm, L. K., *et al.* "Strong Loophole-Free test of Local Realism." *Physical Review Letters* 115 (2015) 250402
- Shor, P. "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer." *Proceedings of the 35th Annual Symposium on Foundations of Computer Science, Santa Fe, NM, Nov. 20-22, 1994*, pp. 124-134. (Revised and expanded versions of this paper subsequently appeared on the arXiv preprint server and in *SIAM Journal of Computing* 26 (1997) pp. 1484-1509)
- Smirnov, A.Y., *et al.* "Modelling chemical reactions using semiconductor quantum dots." *Europhysics Letters* 80 (2007) 67008
- Torrontegui, E. *et al.* "Simulation of quantum collinear chemical reactions with ultracold atoms." *Journal of Physics B* 44 (2011) 195302
- Van Bibber, K. and G. Carosi. "Status of the ADMX and ADMX-HF experiments." *Proceedings of the 8th Patras Workshop on Axions, WIMPs, and WISPs.* (2012) ISBN 978-3-935702-69-0