Future Directions in Quantum Computation: Framing Document

This is an exciting time for quantum information processing technology and science. Advances in quantum computing indicate that over the next 5-10 years we will have general purpose quantum computers with 50-500 qubits. Such devices could perform computations that conventional classical computers cannot perform. Techniques for quantum communication and for interfacing quantum communication systems with quantum information processors have reached the point where a prototype quantum internet can be constructed, suggesting that a wide range of quantum communication protocols will be realized. Finally, quantum metrology represents the gold standard for precision measurement: the world's most accurate clocks employ quantum logic to attain unprecedented precision, and next-generation LIGO will use quantum enhancements to attain significantly higher precision for detection of gravitational waves.

We have been given an opportunity by the Office of Secretary of Defense to assess the current state and future outlook for this rapidly developing field, so that DoD and other federal agencies can plan for future research investments and programs. Novel technologies for quantum computing, quantum communication, and quantum sensing have the potential to revolutionize the fields of computation, secure communication, detection, and measurement, ~~which are areas of critical importance to the DoD and its future mission.~~ The goal of the workshop is to assess the state of current quantum information processing technologies, to map out their future development, and to identify applications of these technologies.

Perhaps the most dramatic development in the field of quantum computation is the development of scalable architectures for quantum computation based on highly coherent quantum bits. Ion traps and atom-optical quantum information processors have been making steady progress towards larger scale quantum devices consisting of tens to hundreds of qubits for general purpose quantum computing, and hundreds to thousands of qubits for special-purpose devices such as quantum simulators based on optical lattices. Superconducting quantum computers are making rapid progress: there is a clear path to constructing general purpose quantum computers with hundreds of high-fidelity quantum bits controlled and measured by precise on-chip superconducting electronics. Special-purpose superconducting quantum information processors consisting of thousands of highly coherent qubits with tunable non-stoquastic couplings will soon be available for the purposes of Hamiltonian quantum computing, quantum simulation, and quantum annealing. The next generation of coherent quantum information processors will have the ability to perform 'mid-scale' quantum computations of $O(10^4)$ quantum operations on $O(10^2)$ qubits, without having to resort to quantum error correction. For larger computations, quantum error correcting codes have been demonstrated, pointing to the construction of large-scale quantum computers that operate in a fully fault tolerant fashion.

What will we do with these powerful devices? The upcoming generation of quantum information processors will be able to perform large-scale quantum simulations for quantum chemistry and two-dimensional solid-state quantum systems. Such quantum simulations will allow the exploration of a wide variety of fundamental quantum dynamics that lie out of the reach of classical simulations. At the same time, the use of mid-scale quantum computers and Hamiltonian quantum information processors will allow the implementation of quantum solutions to optimization and constraint satisfaction problems. The ability of quantum computers to perform basic linear algebra operations such as finding eigenvectors/eigenvalues and matrix inversion suggest that quantum computers with $O(10^2)$ qubits and capable of $O(10^4)$ coherent operations could supply a significant advantage over classical computers for problems of pattern recognition and machine learning. The workshop will map out the paths to development and construction of such mid-scale quantum information processors, and will explore their multiple applications.

At the same time as quantum computing technologies have leaped ahead, significant breakthroughs have taken place in the field of quantum communication to connect small-scale quantum information processors over long distances. Quantum repeaters for quantum communication channels to distribute entanglement over long distances will soon be a reality. In addition to expanding significantly the capacity for secure communications, such a prototype quantum internet will allow a wide variety of distributed quantum information protocols to be put into practice. Quantum secret sharing, quantum data locking, distributed quantum games and quantum decision making protocols will become possible. A particularly important question is the application of highly precise quantum clocks connected by quantum communication channels: such a 'world quantum clock' holds out the promise for a dramatic increase in the precision of GPS. The workshop will explore the potential applications of the protoype quantum internet, and will map out the path to its realization.

The most powerful current application of quantum information technologies is in the field of precision measurement and sensing. For almost a decade now, the most precise atomic clock has been the NIST quantum logic clock that uses quantum logic to entangle optical and microwave transitions, yielding orders of magnitude of advance in precision over previous atomic clocks. Quantum information processing using Nitrogen-Vacancy (NV) centers in diamond takes advantage of quantum coherence and entanglement to deliver highly precise magnetometry. Entangled superconducting qubits can be used to construct ultra-precise electromagnetic sensors and detectors. Quantum optical devices hold out the promise of quantum enhanced sensing, detection, and ranging. Perhaps the most dramatic expected use of quantum effects in metrology will be the injection of squeezed vacuum into next-generation LIGO, which has the potential to increase the sensitivity of gravitational wave detection by more than an order of magnitude. The workshop will map out the upcoming developments of quantum sensing and metrology, and will explore novel applications.

~~Of interest to the DoD,~~ in addition to a perspective on new opportunities for quantum information processing are answers to questions such as:

– ~~Why invest now?~~

– ~~What are the implications of research investments~~ in quantum information technology and science ~~for~~ the fields of computation, communication, measurement and sensing?

– ~~What developments are on horizon within 5 years? 10 years? Or 20 years and beyond?~~