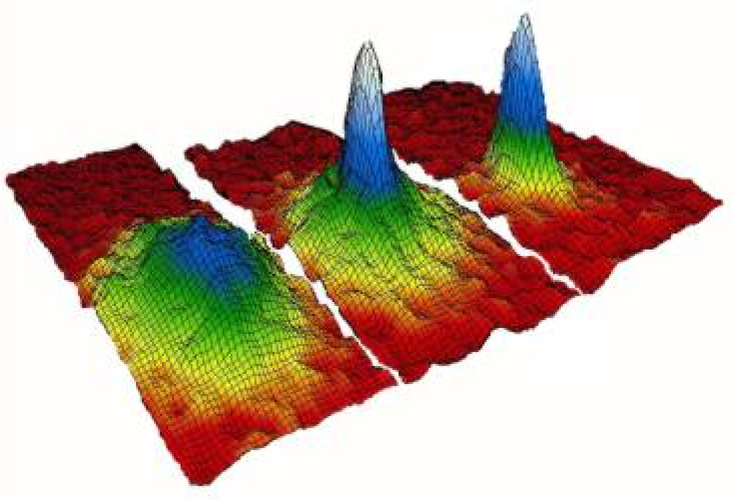
Quantum Information

As the field of information technology continues to mature, it derives great benefit from remarkable advances that have been enabled through the development of ever-smaller electronic devices, at length scales reaching less than 10 nm. There arise, however, serious questions concerning the future of the overall process of microminiaturization. At these small length scales quantum properties begin to emerge. One approach to microminiaturization is to incorporate dissipation and decoherence into device design in order to create small electronic devices that have properties similar to their larger counterparts. Alternatively, one can make use of the quantum properties in order to gain new capabilities. In one approach addressing this eventuality, the NIST Physics Laboratory has embarked on a pioneering research program in quantum information science that is aimed at creating a new paradigm for information processing and computing for the 21st century based on the physics of quantum systems.



Velocity distribution in a Bose-Einstein condensate.

In a manner roughly analogous to the conventional processing of information via present-day silicon-based computers, quantum information considers the processing of information through the controlled manipulation of so-called quantum bits or "qubits," according to the rules of quantum physics. Whereas a classical bit can exist in either one of two possible states at any instant in time, conventionally represented as either 0 or 1, a quantum bit can exist *simultaneously* in a coherent quantum superposition of both the 0 and 1 states. Thus, for example, a three-bit register composed of classical bits may at any instant in time represent any one of the digits 0 through 7. Correspondingly, a three-bit quantum register, however, may represent all of the digits 0 through 7 simultaneously.

The real power of quantum logic and quantum information processing lies in the entanglement of the qubits, which permits an exponential increase in the information carrying capacity of systems based on quantum processing. That is, unlike classical information processing where the capacity of the system scales linearly with the number of (classical) bit registers available to the system, quantum information, with entanglement of the qubits, provides for exponential growth in the storage capacity with the number bits. That is, in quantum information processing, the processing capacity scales exponentially as the number of available qubits, as opposed to classical information processing, which scales linearly with the number of classical bits. Thus, a 300-qubit system can store more information in quantum superposition than could be stored classically by using as bits all 10^{80} baryons that make up the entire universe.

Nature March 16, 2000 illustrating quantum entanglement of four beryllium ions confined in an ion trap

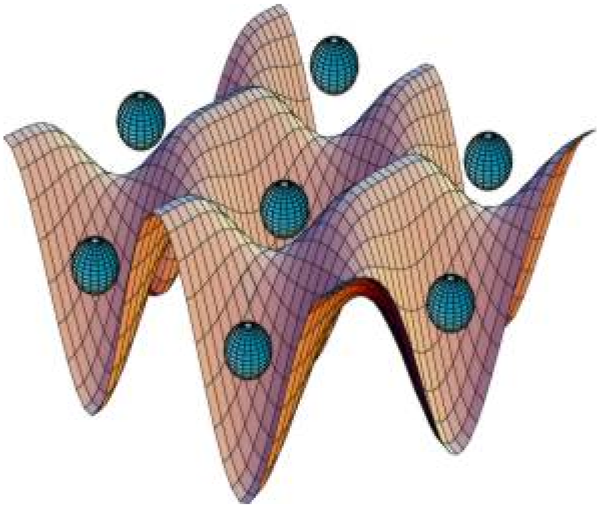
Nature, March 18, 1999 illustrating four-wave mixing with matter waves

Quantum information science offers a new paradigm for information processing, exchange and storage, and provides a basis for the development of quantum computers and physically secure communication; i.e., communication whose resistance to eavesdropping is guaranteed by physical law. Moreover, NIST's program in quantum information science enhances the Institute's long-term goal of creating the basis for metrology whose precision is limited only by quantum uncertainty. Providing a new basis for precision metrology can, for example, lead to further improvements in atomic time and frequency standards.

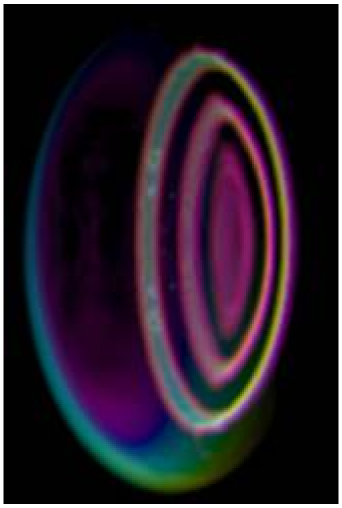
In the area of quantum information science, NIST has built a broad program firmly based on the work of the Physics Laboratory's Ion Storage Group in Boulder, CO, led by David Wineland. A near-term goal of this program is to produce the first (prototype) quantum logic processor consisting of approximately 10 qubits. The prototype device will provide a testbed for demonstrating stabilized quantum memory, quantum error correction, fault-tolerant quantum gate implementation, quantum repeater operation without output coupling, and implementation of optimal quantum strategies for precision measurements. We anticipate that follow-on work will be directed towards the development of an optical interconnect to interface the quantum information devices via an optical fiber. This aspect is essential for long-distance quantum communication where photons appear to be the most appropriate qubit for information transmission. The experimental effort is supplemented by theoretical efforts aimed at developing robust models of these complex systems in order to study and characterize possible sources of error and limitations. This complexity results form the requirement that it is essential for real systems to interact with their environment if one is to manipulate and control them. However, uncontrolled or imperfect interaction of a quantum system with its environment will provide a source of "decoherence" or error that will degrade the system's fidelity.

The primary challenge, therefore, is to construct a logic device that meets the criteria for a quantum processor, namely: state preparation, scalability, two-qubit gates for entangling operations, efficient readout, and small decoherence. The current NIST effort focuses on implementing two-level atomic systems as qubits. These systems have small decoherence, and are capable of entanglement, which is a necessary requirement for a quantum gate. The use of atomic systems will be pursued on two fronts, with the Ion Storage Group focussing on trapped-ion technology, and the Laser Cooling and Trapping Group and the JILA Atomic Physics Group developing neutral-atom systems.

The two approaches have different strengths with respect to the criteria stated above. Controlling decoherence even in these "natural qubit" systems is a technical challenge since one must maintain the ability to interface with the processor while simultaneously isolating the atoms from decoherence processes. Moreover, controlling decoherence while scaling the system is necessary in order to build a high-fidelity processor that is capable of entangling all the qubits via "on demand" entanglement of any two qubits. The immediate objectives of the trapped-ion work are to overcome the effects of motional heating, which degrades the fidelity of the data-bus qubit, and to multiplex ion-trap systems by transferring ions (quantum information) between different locations. The latter goal is essential to scalability of quantum information systems based on ion trap implementation, while the former addresses the requirement for small decoherence. The neutral-atom program will test possible implementations of quantum logic operations in optically confined systems. The near-term objectives include: uniformly loading an optical lattice with a predetermined number of atoms, addressing the individual qubits in an optical lattice, and entangling the atoms confined in lattice sites. A key technical difficulty of the neutral-atom/optical lattice approach is addressibility and efficient readout.



Atoms trapped in an optical lattice



Soliton produced by phase-printing a Bose-Einstein condensate

The efforts of both experimental phases are complemented by a corresponding theoretical effort that focuses on providing detailed modeling of experimental systems, identifying fundamental limitations due to the effects of noise and decoherence, and evaluating alternative approaches for implementing quantum logic in trapped-atom systems, such as lithographically-produced optical and magnetic traps and waveguides.