Quantum Computation with Ultrafast Laser Pulse Shaping

Debabrata Goswami

Debabrata Goswami is at the Department of Chemistry, Indian Institute of Technology, Kanpur, where he explores the applications of ultrafast shaped pulses to bio-imaging, coherent control, high-speed communication and quantum computing.

Quantum computing exploits the quantum mechanical nature of matter to exist in multiple possible states simultaneously. Building up on the digital binary logic of bits, quantum computing is built on the basis of interacting two-level quantum systems or 'qubits' that follow the laws of quantum mechanics. Addressability of the quantum system and its fragility to fidelity are the major issues of concern, which if addressed appropriately, will enable this new approach to revolutionize the present form of computing.

Introduction

Today's computer represents the culmination of years of technological advancements beginning with the early ideas of Charles Babbage (1791-1871) and eventual creation of the first computer by German engineer Konrad Zuse in 1941. Surprisingly however, the high speed modern day computer is fundamentally no different from its gigantic 30 ton ancestors, which were equipped with some 18000 vacuum tubes and 500 miles of wiring!

Going to 'nano' as miniaturization continues has led to a new paradigm for computing, namely the idea of a computational device based on quantum mechanics. The idea emerged when in the 1970's and early 1980's, scientists such as Charles H Bennett of the IBM Thomas J Watson Research Center, Paul A Benioff of Argonne National Laboratory, David Deutsch of the University of Oxford, and the late Richard P Feynman of the California Institute of Technology, were pondering on the fundamental limits of computation. They understood that if technology continued to abide by Moore's Law[1], then the continually shrinking size of circuitry packed onto silicon chips would eventually reach a point where individual elements would be no larger than

Keywords
Qubit, quantum information, NMR, decoherence, programmable ultrafast pulse shaping.

a few atoms. Here a problem arose, because at the atomic scale, the physical laws that govern the behavior and properties of the circuit are inherently quantum mechanical in nature, not classical. This then raised the question of whether a new kind of computer could be devised based on the principles of quantum physics.

Feynman was among the first to attempt to provide an answer to this question by producing an abstract model in 1982 that showed how a quantum system could be used to perform computations. He also explained how such a machine would be able to act as a simulator for quantum physics. In other words, a physicist would have the ability to carry out experiments in quantum physics inside a quantum mechanical computer. Later, in 1985, Deutsch realized that Feynman's assertion could eventually lead to a general purpose quantum computer and published a crucial theoretical paper showing that *any* physical process, in principle, could be modeled perfectly by a quantum computer. Thus, a quantum computer would have capabilities far beyond those of any traditional classical computer. After Deutsch published this paper, the search began to find interesting applications for such a machine.

Unfortunately, all that could be found were a few rather contrived mathematical problems, until Peter Shor circulated in 1994 a preprint of a paper in which he set out a method for using quantum computers to crack an important problem in number theory, namely factorization. He showed how an ensemble of mathematical operations, designed specifically for a quantum computer, could be organized to enable such a machine to factor huge numbers extremely rapidly, much faster than is possible on conventional computers. With this breakthrough, quantum computing transformed from a mere academic curiosity directly into a national and world interest.

Quantum Information and Computing

A quantum computer manipulates qubits by executing a series of quantum gates, each a unitary transformation acting on a

[1] The original Moore's Law derives from a speech given in 1965 by Gordon Moore (later cofounder of Intel), in which he observed that the number of micro-components of the lowest manufacturing cost that could be placed in a microchip was doubling every year and that this trend would likely continue into the future. Later, the Law was reformulated to mean that rate. The pace of change has slowed down a bit over the past few years, the definition has changed (with Gordon Moore's approval) to reflect that the doubling occurs only every 18 months.

Peter Shor circulated in 1994 a preprint of a paper in which he set out a method for using quantum computers to crack an important problem in number theory, namely factorization.

The simulation of a quantum computer on a classical one is a computationally hard problem because the correlations among quantum bits are qualitatively different from correlations among classical bits.

single qubit or pair of qubits. In applying these gates in succession, a quantum computer can perform a complicated unitary transformation to a set of qubits in some initial state. The qubits can then be measured, with this measurement serving as the final computational result. This similarity in calculation between a classical and quantum computer affords that in theory, a classical computer can accurately simulate a quantum computer. In other words, a classical computer would be able to do anything a quantum computer can. So why bother with quantum computers? Although a classical computer can theoretically simulate a quantum computer, it is incredibly inefficient, so much so that a classical computer is effectively incapable of performing many tasks that a quantum computer could perform with ease. The simulation of a quantum computer on a classical one is a computationally hard problem because the correlations among quantum bits are qualitatively different from correlations among classical bits.

Thus, for example, a system of 500 qubits, which is impossible to simulate classically, represents a quantum superposition of as many as 2^{500} states. Each state would be classically equivalent to a single list of 500 1's and 0's. Any quantum operation on that system – a particular pulse of radio waves, for instance, whose action might be to execute a quantum gate operation on the 100th and 101st qubits – would simultaneously operate on all 2^{500} states. Hence in one single step, one tick of the computer clock, a quantum operation could compute not just on one machine state, as serial computers do, but on 2^{500} machine states at once! Eventually, however, observing the system would cause it to collapse into a single quantum state corresponding to a single answer, a single list of 500 1's and 0's, as dictated by the measurement axiom of quantum mechanics. The reason this is an exciting result is because this answer, derived from the massive quantum parallelism achieved through superposition, is the equivalent of performing the same operation on a classical super computer with $\sim 10^{150}$ separate processors (which is of course impossible)!!

The field of quantum information processing has made numerous promising advances since its conception, including the building of two- and three-qubit quantum computers capable of some simple arithmetic and data sorting. However, a few potentially large obstacles still remain that prevent us from "just building one," or more precisely, building a quantum computer that can rival today's modern digital computer. Among these difficulties, error correction, decoherence, and hardware architecture are probably the most formidable. Error correction is rather self explanatory, but what errors need correction? The answer is primarily those errors that arise as a direct result of decoherence, or the tendency of a quantum computer to decay from a given quantum state into an incoherent state as it interacts, or entangles, with the state of the environment. These interactions between the environment and qubits are unavoidable, and induce the breakdown of information stored in the quantum computer, and thus errors in computation. Before any quantum computer will be capable of solving hard problems, research must devise a way to maintain decoherence and other potential sources of error at an acceptable level. Thanks to the theory (and now reality) of quantum error correction, first proposed in 1995 and continually developed since, small scale quantum computers have been built and the prospects of large quantum computers are looking up.

Error correction, decoherence, and hardware architecture are probably the most formidable difficulties.

Implementing a Quantum Computer

At this point, only a few of the benefits of quantum computation and quantum computers are readily obvious, but before more possibilities are uncovered, theory must be put to the test. In order to do this, devices capable of quantum computation must be constructed. Quantum computing hardware is however, still in its infancy. The best method of achieving quantum computation experimentally is still unknown, but many methods are being experimented with and are proving to have varying degrees of success. Much of the proposed implementations of quantum computing, and most of the theoretical work, has been aimed at isolated systems such as cavity QED and trapped ions.

Much of the proposed implementations of quantum computing, and most of the theoretical work, has been aimed at isolated systems such as cavity QED and trapped ions.

The most successful current approach takes a completely different radical route namely, the concept of bulk nuclear magnetic resonance (NMR) spectroscopy.

Thus, in the ion trap scheme, each qubit is carried by a single ion held in a linear Paul trap. The quantum state of each ion is a linear combination of the ground state and a particular long-lived metastable excited state. A coherent linear combination of the two levels can survive for a time comparable to the lifetime of the excited state. The relative phase oscillates because of the energy splitting between the levels. The ions are so well isolated that spontaneous decay can be the dominant form of decoherence. One big drawback of the ion trap computer is that it is an intrinsically slow device. The energy-time uncertainty relation ultimately limits its speed. Another idea based on isolated system has been to trap several neutral atoms inside a small high finesse optical cavity. Quantum information can be stored in the internal states of the atoms. But the atoms interact in this case because they all couple to the normal modes of the electromagnetic field of the cavity, instead of the vibrational modes as in the ion trap. By driving transitions with pulsed lasers, one can induce a transition in one atom that is conditioned on the internal state of another atom. Another possibility is to store the qubit in the polarization of a photon and not in the internal state of an ion. A trapped atom can then be used as the intermediary that causes one photon to interact with another.

Interestingly, however, the most successful current approach takes a completely different radical route. It drops the assumption that the quantum medium has to be tiny and isolated from its surroundings and instead uses a sea of molecules to store the information. It is the concept of bulk nuclear magnetic resonance (NMR) spectroscopy(see [1]), where binary operations are inherently possible due to the two-state nature of the spin-states. When held in a magnetic field, each nucleus within a molecule spins in a certain direction, which can be used to describe its state; spinning upwards can signify a 1 and spinning down, a 0. NMR techniques can be used to detect these spin states and bursts of specific radio waves can flip the nuclei from spinning up (1) to spinning down (0) and vice-versa. The quantum computer in this technique is the molecule itself and its qubits are the nuclei within the molecule. This technique does not use a single molecule to perform the computations; it instead uses a whole 'mug' of liquid molecules. The advantage of this is that although the molecules of the liquid bump into one another, the spin states of the nuclei within each molecule remain unchanged. Decoherence is still a problem, but the time before the decoherence sets in is much longer than in any other technique so far. The binary operations are inherently possible due to the two-state nature of the spin-states. Recently, the potential of constructing a six-qubit quantum computer has been demonstrated with the NMR technique. Unfortunately, for the implementation of realistic calculations on a quantum computer, a large number of qubits will be necessary (about 10^5). Though these devices have had mild success in performing interesting experiments, the technologies each have serious limitations. Ion trap computers are limited in speed by the vibration frequency of the modes in the trap. NMR devices have an exponential attenuation of signal to noise as the number of qubits in a system increases. Cavity QED is slightly more promising; however, it has only been demonstrated with a few qubits.

For the implementation of realistic calculations on a quantum computer, a large number of qubits will be necessary.

Future Approaches

In this quest for new approaches to quantum computing, our research work at Indian Institute of Technology, Kanpur, which has been seeded by the effort started at Tata Institute of Fundamental Research, Mumbai, presents a straightforward method for the modulation of the phase of a laser pulse to an atom or molecule. Such approaches are essentially optical analogues of the NMR scheme. The problem of *scalability* is minimal once such optical techniques are employed. This is because, for optical transitions, the energy difference between the ground state and excited state is large compared to kT even at room temperature (typically, $kT = 208\ cm^{-1}$ at $T = 300K$). Such optical schemes would require feedback-loop computer controlled pulse shaping as has been demonstrated by Bucksbaum and coworkers [2] in the case of an excited state of Cesium atom. They demonstrated that it is possible to store information as a

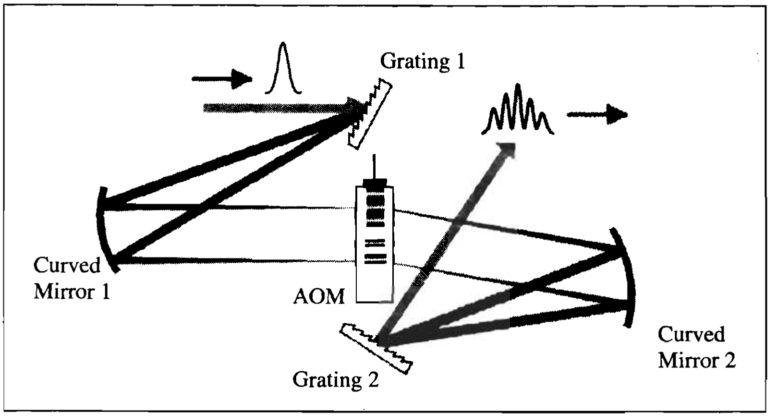

Figure 1. Schematic of an Acousto-Optic Modulator (AOM) based ultrafast pulse shaping technology that allows arbitrary programmable pulse shaping at high repetition rate of ~10^6 Hz.

quantum phase in one or more flipped state, which could be subsequently retrieved in a single step in agreement with Grover's quantum search algorithm. Doing such local manipulations on an atom or molecule is equivalent to doing spectroscopy. However, as the levels of complexity increase, they essentially turn into 'coherent control' problems(see [3]), which involve the study of possible control on the future of any coherent light-matter interaction. These experiments have established the promise on the applications of ultrafast pulse shaping technology (*Figure* 1) and 'coherent control' developments to practical quantum computing problems(see [4]) in the future.

Conclusion

At present, quantum computers and quantum information technology remains in its pioneering stage. At this very moment obstacles are being surmounted that will provide the knowledge needed to thrust quantum computers up to their rightful position as the fastest computational machines in existence. Quantum hardware, on the other hand, remains an emerging field, but the work done thus far suggests that it will only be a matter of time before scalable systems become possible to be implemented. Thereby, quantum computers will emerge as the superior computational devices at the very least, and perhaps one day make today's modern computer obsolete. Quantum computation has its origins in highly specialized fields of theoretical physics, but its future undoubtedly lies in the profound effect it will have on the lives of all mankind.

Suggested Reading

[1] N Gershenfeld and I Chuang, *Science*, Vol. 275, p.350, 1997.
[2] J Ahn, T C Weinacht and P H Bucksbaum, *Science*, Vol.287, p.463, 2000.
[3] D Goswami, *Physics Reports*, Vol. 374, p. 385, 2003.
[4] D Goswami, *Phys. Rev. Lett.*, Vol. 88, p.177901, 2002.

Address for Correspondence
Debabrata Goswami
Coordinator
Quantum Computing
Femtosecond Laboratory
Indian Institute of Technology
Kanpur 208 016, India.
Email:dgoswami@iitk.ac.in