A Potentially Realizable Quantum Computer

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Arrays of weakly coupled quantum systems might compute if subjected to a sequence of electromagnetic pulses of well-defined frequency and length. Such pulsed arrays are true quantum computers: Bits can be placed in superpositions of 0 and 1, logical operations take place coherently, and dissipation is required only for error correction. Operated with frequent error correction, such a system functions as a parallel digital computer. Operated in a quantum-mechanically coherent manner, such a device functions as a general-purpose quantum-mechanical micromanipulator, capable of both creating any desired quantum state of the array and transforming that state in any desired way.

Technological progress is beginning to make practical a question that was previously academic: What are the fundamental physical limits on computation? Landauer's result (*1*), that the only logical operations that necessarily require dissipation are irreversible ones, has led to designs for reversible, dissipationless logic devices (*2*), to the discovery that computation can be carried out with the use of reversible logic alone (*3–4*), and to proposals for computers in which bits, the fundamental quanta of information, are registered by true quantum-mechanical quanta such as spins (*5–10*). Up to now, proposals for quantum-mechanical computers have relied on "designer Hamiltonians," specially constructed to allow computation, which do not necessarily correspond to any physical system. This report, in contrast, proposes a class of quantum computers that might actually be buildable.

The proposed computers are made of arrays of weakly coupled quantum systems. Computation is effected by subjecting the array to a sequence of electromagnetic pulses that induce transitions between locally defined quantum states. In one dimension, for example, the computer might consist of localized electronic states in a polymer; in two dimensions, quantum dots in a semiconductor; in three dimensions, nuclear spins in a crystal lattice. Operating at Landauer's limit, with dissipation required only for error correction, the systems detailed here are true quantum computers as envisioned by Deutsch (6): Bits can be placed in superpositions of 0 and 1, quantum uncertainty can be used to generate random numbers, and states can be created that exhibit purely quantum-mechanical correlations (*5–10*).

The idea of exploiting quantum effects to build molecular-level computers is not new (*11–13*). The proposal detailed here relies on the selective driving of resonances, a method used by Haddon and Stillinger (*11*) to induce logic in molecules and by Obermayer, Teich, and Mahler (*14*) to induce a parallel logic in arrays of quantum dots. Here, this method is used to give quantum-mechanically coherent computation. Consider a one-dimensional array of quantum-mechanical units (*ABC ABC* . . .): for example, a heteropolymer in which each unit possesses a long-lived excited state. For each unit *A*, *B*, or *C*, call the ground state 0 and the excited state 1. In the absence of any interaction between the units, it is possible to drive transitions between the ground state and the excited state of units of a given type, *B* say, by shining light on the array at the resonant frequency ω_B of the transition between the ground and excited states of *B* (*15, 16*). Let the light be in the form of a π pulse, so that $\hbar^{-1} \int \vec{\mu}_B \cdot \hat{e}\mathscr{E}(t)dt = \pi$, where $\vec{\mu}_B$ is the induced dipole moment between the ground state and the excited state, $\hat{e}$ is the polarization vector for the light that drives the transition, and $\mathscr{E}(t)$ is the magnitude of the pulse envelope at time *t*. The effect of this pulse is to take each *B* that is in the ground state and put it in the excited state, and to take each *B* in the excited state and put it in the ground state—to flip the *B* bits. If *A*, *B*, and *C* have distinct resonant frequencies, then the *A*'s and *C*'s are unaffected by the pulse.

Now suppose that there are local interactions between the units of the array. In a polymer, for example, the interactions could arise from overlap between electron wave functions from unit to unit, from van der Waals forces, from changes in the local structure of the polymer, or from induced or permanent multipole coupling. Almost any local interaction will do: Consider first nearest-neighbor interactions given by arbitrary (not "designer") interaction Hamiltonians H_{AB}, H_{BC}, and H_{CA}. The effect of the terms in the interaction Hamiltonians that are diagonal in the logical states is to shift the energy levels of each unit as a function of the energy levels of its neighbors: The resonant frequency ω_B, for instance, takes on a value ω^B_{01} if the A on its left is in its ground state and the C on its right is in its excited state. Some of the off-diagonal terms make each of the logical states of the array the sum of energy eigenstates within a band: As long as this bandwidth is smaller by several orders of magnitude than the bandwidth of the π pulse that effects the switching, so that the propagation time for excitons along the array is much longer than the length of the π pulse, then the effect of these off-diagonal terms can be ignored. Other off-diagonal terms introduce occasional errors in switching.

If the resonant frequencies for all transitions are different for different values of a unit's neighbors, then the transitions can be driven selectively: When a π pulse with frequency ω^B_{01} is applied to the array, all the *B*'s with an $A = 0$ on the left and a $C = 1$ on the right will switch from 0 to 1 or from 1 to 0. If all transition frequencies are different, these are the only units that will switch. Each unit that undergoes a transition coherently emits or absorbs a photon of the given frequency: No dissipation takes place in the switching process.

Driving transitions selectively with resonant π pulses induces a parallel logic on the states of the array: A particular resonant pulse updates the states of all units of a given type as a function of the unit's previous state and the states of its neighbors. All units of the given type with the same values for themselves and their neighbors are updated in the same way. That is, applying a resonant pulse to the polymer effects the action of a cellular automaton rule on the states of units of the array (*14, 17*). The effect of longer range interactions, such as dipole-dipole coupling, is simply to extend the size of the neighborhood on which the cellular automaton rule depends (for such systems to function as described, care must be taken in their operation to ensure that two interacting units of the same type are never flipped by the same pulse).

Sequences of resonant pulses allow one to load information onto the array, to process it, and to unload results. There is one unit that can be controlled independently: the unit on the end (*14*). Because it has only one neighbor, this unit in general has a resonant frequency different from all other units. As a result, by supplying π pulses of the end unit's resonant frequency, one can switch the unit from 0 to 1 on its own and load arbitrary bits of information onto the end of the array.

The sequence of π pulses with frequencies ω^A_{01}, ω^A_{11}, ω^B_{10}, ω^B_{11}, ω^A_{01}, and ω^A_{11} causes each *A* in the array (except the *A* on the end) to exchange or swap the bit of information that it carries with the bit of information carried by the *B* on its right. Continued swaps between different types of units, interspersed with manipulations of the end unit, allow one to load any se-

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quence of bits desired onto the A's and B's in the array. For higher dimensional arrays, information can be loaded first onto corner units, then moved along edges by swapping, as above, then moved onto faces, and so on.

Information that has been loaded onto the array can be processed by a variety of schemes. For example, the sequence of π pulses with frequencies ω_{01}^{A}, ω_{11}^{A}, ω_{11}^{B}, ω_{01}^{A}, and ω_{11}^{A} causes each A in the interior of the array to swap the bit of information that it carries with the B on its right if and only if the C in the triple ABC has the value 1. That is, this sequence of pulses effects the operation of a Fredkin gate on each triple ABC, with C as the control bit (*4*). It is well known that Fredkin gates can supply the logical operations AND, OR, NOT, and FANOUT and so can be wired together to give any desired logic circuit. Unfortunately, on the face of it, the array has no wires to move information about.

Fortunately, the proper sequence of pulses allows the creation of a "wire," even though the hardware of the device possesses no physical wires (Fig. 1). Such wires allow one to move into a single triple ABC any three bits on which one desires to operate with a Fredkin gate. Stringing together of these wires, together with operation of Fredkin gates, allows one to create any desired logic circuit. In addition, by formatting data as in Fig. 1 and multiplying the number of control units, one can make the array function as a parallel computer (Fig. 2). Note that, except for the pulses that actually load a bit onto the end unit, the sequences that move and process information are independent of the data.

The proposed device is capable of purely quantum-mechanical information-processing capacities above and beyond the conventional digital capacities already presented. One of the most important of these capacities is that bits can be placed in superpositions of 0 and 1 by the simple application of pulses at the proper resonant frequencies but at a length different from that required to fully switch the bit. Such bits have a number of uses, including the generation of random numbers. If in loading information onto the array, one applies a $\pi/2$ pulse of length $\pi/(2\omega_{0}^{A:end})$ at the resonant frequency $\omega_{0}^{A:end}$ of the end unit instead of applying a π pulse, the A unit on the end will change to the state $1/\sqrt{2}(|0\rangle - |1\rangle)$. A subroutine that calls this bit will get the value 0 or 1, each with probability 1/2. A second π pulse of frequency ω_{10}^{B} applied at the proper time then puts the first two units in the state, $1/\sqrt{2}(|00\rangle - |11\rangle)$, and a third π pulse of frequency ω_{10}^{C} applied at the proper time puts the first three units in the state $1/\sqrt{2}(|000\rangle - |111\rangle)$. This last state contains purely quantum-mechanical Einstein-Podolsky-Rosen correlations that give extreme violation of Bell's inequalities (*18, 19*).

	A	B	C	A	B	C	A	B	C	A	B	C
1	x_1	0	1	x_2	0	0	x_3	0	0	x_4	0	0
2	0	x_1	1	x_2	0	0	x_3	0	0	x_4	0	0
3	0	0	0	x_2	0	0	x_3	0	0	x_4	x_1	1
4	0	0	0	x_2	0	0	x_3	0	0	x_1	x_4	1
5	0	x_4	1	x_2	0	0	x_3	0	0	x_1	0	0
6	x_4	0	1	x_2	0	0	x_3	0	0	x_1	0	0

Fig. 1. Two wires. In (1), data is encoded in the A units in a section, and all the B's and C's, except for one unit, are set to 0. Call the unit in which C = 1 the control unit. In (2), the array has been subjected to a series of pulses that realizes a Fredkin gate on each triple ABC. The only triple affected is the one in which the control unit sits: Here, the bit of data has been moved to the B unit. In (3), the information in the BC units has been moved 3 triples to the right by the information-swapping process given in the text. In (4), the operation of a Fredkin gate on all triples has swapped x_1 with x_4; all other triples are unchanged. In (5), the information in the BC units has been moved back three triples to the left. In (6), the operation of a Fredkin gate on all triples has restored x_4 to the A unit in the triple. The first three configurations show the action of the first wire, moving x_1 adjacent to x_4; the second three configurations show the action of the second wire, moving x_4 back to x_1's old place. The set of pulses transporting the data is independent of the data being transported.

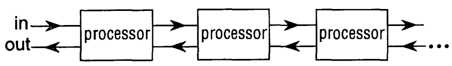

Fig. 2. The architecture of the parallel computer. Input and output take place at the processor on the end. Each parallel processor has the same circuitry, realizing any desired logical function. After each processor cycle, an arbitrary number of bits are exchanged with the processors on the left and on the right. The two-dimensional version of the computer has an analogous form.

This example suggests, and an inductive proof shows (*20*), that the proper sequence of pulses, applied at the proper times, puts the first N units in any desired quantum state. A second sequence of pulses effects any desired unitary transformation on those N units. The proposed device is not only a universal digital computer, but a general purpose quantum-mechanical micromanipulator (it is instructive to compare this sort of micromanipulation with that performed by a scanning tunneling electron microscope). The example given clearly shows that one can realize Deutsch's "quantum parallelism" by preparing the array in a superposition of program states and then operating the array as a digital computer (*6*). Of course, the number of steps over which coherent superpositions of computational states can be maintained is limited by interactions with the environment, which induce phase randomization and decoherence.

All the processes described so far are logically reversible—the effect of a sequence of π pulses can be undone simply by applying the same sequence in reverse order—and dissipationless. If in addition to a long-lived excited state, any of the units possesses an excited state that decays quickly to a long-lived state, this fast decay can be exploited to provide data readout and error correction. For example, each unit could have an additional excited state, 2, that decays to the ground state, 0, in an amount of time short compared with the time in between pulses. To read the value of a bit, one simply moves that bit to the unit on the end and then applies a pulse that drives the transition between that unit's first excited state, 1, and the short-lived excited state, 2. If the bit reads 1, then the unit will emit a photon of distinctive frequency. If the bit reads 0, no photon will be emitted. Because of low efficiencies of photon detection, several copies of the bit may have to be read to make an accurate determination of its value.

Error correction is a logically irreversible process and requires dissipation if errors are not to accumulate (*1*). The sequence of π pulses with frequencies $\omega_{00}^{B}(12)$, $\omega_{11}^{B}(01)$, $\omega_{11}^{B}(12)$, and $\omega_{11}^{B}(01)$ restores each B to the state 0 if its neighbors are 0 and to 1 if its neighbors are 1 [$\omega_{11}^{B}(12)$, for example, is the resonant frequency of the transition between the states 1 and 2 of B, given that B's neighbors are in the state 11; pulses that drive the transition to the short-lived state 2 need not have a precisely timed lengths, provided that they are long enough to drive the transition efficiently]. Swapping the information in the A's with the B's and repeating this restoration process, then swapping the information in the B's with the C's and repeating the restoration process yet again has the following effect: If a majority of the bits ABC are 0, ABC goes to 000; if a majority are 1, ABC goes to 111.

One can expand this simple error-correcting process into a more powerful error-correction routine by having each bit stored in 3M copies, having these perform majority voting in groups of three, as described above, permuting the copies amongst themselves by bit swapping, performing the voting by three again, and so on. This method reduces the probability of error per bit per cycle from $O(\epsilon)$ to $O(\epsilon^{M})$, and results in rapid, robust error correction that is fully compatible with the methods for computation described above. For each wrong value corrected, a photon is emitted incoherently into the environment, destroying quantum coherence for the unit from which it was emitted. In contrast to the switching of bits with π pulses, in which photons are emitted and absorbed coherently, the correction of errors with the use of fast decays is inherently dissipative.

Arrays of pulsed, weakly coupled quantum systems provide a potentially realizable basis for quantum computation. The basic unit in the array could be a quantum dot, a nuclear spin, a localized electronic state in a polymer, or any multistate quantum system that interacts locally with its neighbors and can be compelled to switch between states with resonant pulses of light. Many variations on the scheme presented here exist: The arrays could be two- or three-dimensional, for example, or the switching process could take place through intermediate states with the use of multiple pulses (*14*). The primary technical problems in the construction and operation of such a computer are the identification of man-made or natural systems with appropriate long-lived localized states and the delivery of the proper sequence of accurate pulses. If they can be built, the devices will combine digital and quantum analog capacities to allow the creation and manipulation of complicated many-bit quantum states and to probe the limits set by the fundamental physics of computation.

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A UV-Sensitive Mutant of *Arabidopsis* Defective in the Repair of Pyrimidine-Pyrimidinone(6-4) Dimers

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Plants are continually subjected to ultraviolet-B (UV-B) irradiation (290 to 320 nanometers) as a component of sunlight, which induces a variety of types of damage to the plant DNA. Repair of the two major DNA photoproducts was analyzed in wild-type *Arabidopsis thaliana* and in a mutant derivative whose growth was sensitive to UV-B radiation. In wild-type seedlings, repair of cyclobutane pyrimidine dimers occurred more slowly in the dark than in the light; repair of this photoproduct was not affected in the mutant. Repair, in the dark, of pyrimidine-pyrimidinone(6-4) dimers was defective in the UV-sensitive mutant.

The developmental strategy of plants differs from that of animals in a way that enhances the beneficial effects of random mutagenesis and diminishes its harmful effects (*1, 2*). Although progress has been made in the genetics and biochemistry of repair in the single-cell green alga *Chlamydomonas* (*3*), studies of DNA repair in higher plants have been relatively limited (*4*). Many early studies presented negative results that led to the suggestion that DNA repair does not occur in plants. Both photorepair and excision repair of UV-induced photoproducts have been demonstrated in phytoplankton (*5*) and in several higher plants (*6*). A cyclobutane pyrimidine dimer photolyase activity has been observed in *Arabidopsis thaliana* (*7*).

A complete understanding of the various repair pathways in plants requires an integrated biochemical, molecular, and genetic approach. There has been, to our knowledge, no report of a mutant in any higher plant that is specifically defective in DNA repair, so we initiated a search for DNA repair mutants of *Arabidopsis*. To increase the penetration of UV light through the plant tissue, we used plants homozygous for the mutation *tt5* [*transparent testa* (*8*)] for all experiments. This stock is derived from the Landsberg *erecta* ecotype and is defective in the production of UV-absorbing flavonoid pigments. We mutagenized seeds (termed the M1 or primary mutagenized population) by soaking them in 0.3% ethylmethane sulfonate (EMS), then grew them to maturity, allowed them to self-pollinate, and harvested them in bulk. The seeds resulting from the self-pollination of the M1 plants, termed the M2 population, carry EMS-induced mutations in either the heterozygous or homozygous state. The M2 seeds were sown and self-pollinated, and the mature plants were harvested individually to yield M2 "families." Any M2 plant that is homozygous for a mutation will produce, after self-pollination, a family of progeny in which every individual is homozygous for that mutation. A sample of seeds from each M2 family was tested for sensitivity to UV by analysis of root growth after exposure to UV light.

Approximately 20 seeds from each M2 family were placed on a nutritive agar plate (*9*) and incubated at 22°C under light filtered through orange polyvinyl chloride [photosynthetically active radiation (PAR) was equal to 5 μmol/m^2·s]. Plates were incubated on edge (vertically), and the roots of the seedlings grew downward across the surface of the agar. After 3 days, half of each row of seedlings was exposed to 0.5 kJ/m^2 of UV-B from a UV transilluminator. After irradiation, the plates were rotated by 90° and incubated overnight in complete darkness. Because the plate was rotated, any new growth (after UV-B irradiation) was at right angles to the old growth. Families made up of seedlings that continued to grow on the unirradiated side of the plate but failed to grow on the irradiated side were scored as UV-sensitive (Fig. 1A). Families that uniformly expressed a UV-sensitive phenotype were propagated and backcrossed to their progenitor.

Two UV-sensitive families were detected in a screen of over 2000 mutagenized families. The UV-sensitive phenotype in both of these isolates segregated as a single recessive mutation located approximately

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