showed that a neglect patient's failure to explore the side of space contralateral to the lesion could be attributed to a failure to form and retrieve a representation of that side of space, rather than to any perceptual failure. Experiments with monkeys, in which one hemisphere of the brain was deprived of the visual information (although cortically completely intact) that would enable that hemisphere to form a representation of the contralateral side of space, gave further support to this representational account of neglect (*2*).

Neglect and amnesia are radically different clinical syndromes, and the point of this comparison is not to blur the distinction between them. Rather, the point is to suggest that widespread cortical networks spanning temporal, frontal, and parietal lobes subserve both memory and attention. The different clinical syndromes arise from different kinds of disruption to the long-range axonal communication among parts of the brain. This view contrasts with the traditional view of cortical localization of function, in which cognitive functions such as attention and memory are supposed to be subserved by spatially segregated areas of cortex. Understanding subcortical control of cortical plasticity in terms of widespread cortical networks, rather than assigning discrete parcels of cognitive function to discrete cortical areas, will enhance our current understanding of memory, learning, and other cognitive functions.

References

1. M. Thiebaut de Schotten *et al.*, *Science* **309**, 2226 (2005).
2. D. Gaffan, J. Hornak, *Brain* **120**, 1647 (1997).
3. D. Gaffan, *Philos. Trans. R. Soc. London Ser. B* **357**, 1111 (2002).
4. D. Gaffan, A. Parker, A. Easton, *Neuropsychologia* **39**, 51 (2001).
5. A. Easton, D. Gaffan, *Neuropsychologia* **39**, 71 (2001).
6. A. Easton, R. M. Ridley, H. F. Baker, D. Gaffan, *Cereb. Cortex* **12**, 729 (2002).
7. E. Bisiach, C. Luzzatti, D. Perani, *Brain* **102**, 609 (1979).
8. J. Hornak, *Neuropsychologia* **33**, 305 (1995).

10.1126/science.1119445

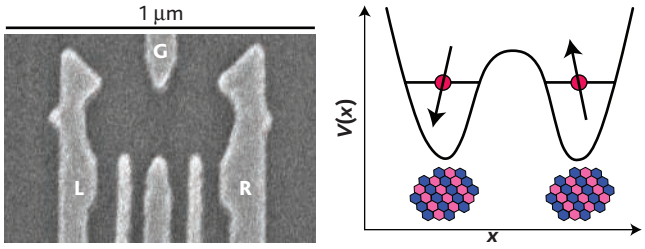
PHYSICS

Double Quantum Dot as a Quantum Bit

David P. DiVincenzo

Quantum dots, solid-state structures that are capable of confining a very small number of electrons, have long been thought of as artificial atoms. With the help of these dots, the tools of device engineering can be used to dissect new atomic physics phenomena. Important advances in recent years have made it routine in several labs to construct the smallest possible dots, each holding exactly one electron. One might expect this artificial "hydrogen" to have extremely simple electronic properties. In fact, because the host crystal is the semiconductor gallium arsenide, the quantum properties of this artificial atom are different from those of its natural analog in one striking respect: The single electron spin, rather than being coupled to the spin of one nuclear proton, is coupled to about a million spins carried by the gallium and arsenic nuclei. This bath of spins has previously been a nuisance, in the sense that it has obscured the quantum coherence of the bare electronic spin. On page 2180, Petta *et al.* (*1*) report that they have used a double quantum dot—in essence, an artificial H_2 molecule—to tame the effect of the nuclear spins. The results suggest novel ways in which the physics of these nuclear spins may be put to use in the search for a viable quantum computer.

As a result of years of steady improvement, the double-dot device (see the figure) of Petta *et al.* is a superb system for precise control of this artificial H_2 molecule. This is accomplished via the electric potentials of the six electrical leads shown. Overall variation of their potentials (with respect to a ground) sets the number of electrons in the two dots. The low-lying electronic states of the two-electron system, as with natural H_2, consist of a spin singlet (S) and three spin triplets (T), in which the two spin $^1/_2$ electrons combine to form either a state of spin quantum number 0 (S) or 1 (the Ts). The energies of these states are tuned in a variety of ways: There is an externally applied magnetic field that splits the triplets. The gate potential (G) controls the tunneling barrier between the two dots. Increasing tunneling increases the energy splitting between S and T, because of the Pauli principle—a singlet can lower its energy by (virtual) tunneling of one of the electrons to the other dot, forming a temporary polarized state; but this state is disallowed if the spin configuration is a triplet. One can also vary the degree of virtual tunneling in an unsymmetrical way, by applying a voltage between electrodes L and R. The virtual tunneling then is only in one direction, but the result is the same: control (in fact, much more reliable control) of the singlet-triplet splitting.



Dot SWAP. Double quantum dot device used by Petta *et al.* (*1*) to coherently manipulate electron spins. G is the gate electrode that controls the barrier between the dots. Voltages on the L and R electrodes control number of electrons in the left and right dots, respectively. Pulsing the potentials on these electrodes causes a SWAP of the spin states of the two dots. [Adapted from (*1*)]

This splitting arises from an effective spin-spin coupling that is very aptly named the exchange interaction in physics, because it does really correspond to an interchange of spin states: As a function of time, $|$up-down$\rangle$ is converted to $|$down-up$\rangle$, and back again. The computer science terminology for this operation is SWAP. SWAP is a very useful primitive for quantum computing (*2*), because it can be done partially, in superposition. In fact, the exchange interaction permits all transformations of the form (*3*) $|a,b\rangle \rightarrow \cos(\theta)\,|a,b\rangle + i\sin(\theta)\,|b,a\rangle$ to be done, for any value of θ, where θ is proportional to the interaction time. (This equation emphasizes that any pair of spin states a and b, pointing in any direction, get SWAPPED, not just the states $|$up$\rangle$ and $|$down$\rangle$.)

If this were the end of the story, the engineering of the quantum computer could be initiated immediately: It is well known how to use "fractional SWAP," either alone or in conjunction with other simple primitives, to implement a quantum algorithm. But nuclear spins, the state of which is not under external control in the device shown in the figure, make the story more complicated, and interesting.

Because each atomic nucleus in the GaAs crystal carries a nuclear spin (with angular momentum quantum number equal to $3/\hbar 2$), a simple calculation shows that the wave function of a single electron in one quantum dot has appreciable overlap with

The author is at the IBM T. J. Watson Research Center, Yorktown Heights, NY 10598, USA. E-mail: divince@watson.ibm.com

about $N = 10^6$ spin-3/2 nuclei. There are some subtle quantum-mechanical aspects to the interaction of the electron with these nuclei (*4*), but one obvious, large, essentially classical effect has been evident in several recent experiments: At any instant in time, each nuclear spin has a projection along the direction of the external magnetic field, adding or subtracting to the total effective field. The value of this Overhauser field can be enormous: If all Ga and As nuclei were maximally aligned with the external field, they would add about 5 T to it. The actual value in the experiment is much smaller, because the direction of each nuclear spin is essentially random (the temperature of the experiment, 100 mK, is "high" as far as the nuclei are concerned). But each dot has a random statistical excess or deficit of Overhauser field, which scales as $\sqrt{N}$, seen by the electrons as a $\approx$ 2-mT, slowly fluctuating field. These variations cause the observed decoherence time of the electron spin to be very short, about 10 ns.

Reenter SWAP, to erase the effect of this slowly fluctuating field, and greatly extend the coherence times of the two-spin states in the double-dot system. In the experiment, at time $t = 0$, the system can be set in the S state. But over time it acquires a random admixture of a triplet state T owing to the difference of Overhauser fields on the two dots. A SWAP is applied at $t = \tau$, interchanging the two spin states. When time 2τ has elapsed, each spin state has effectively spent an equal time in both dots, so that the average Overhauser field seen by both is the same. But S and T do not mix when the effective field is equal in the two dots. What is seen in practice is that, at time 2τ, the random admixture with T is completely undone, and the state becomes again pure S. There is a "singlet echo," in complete analogy to "spin echo" in magnetic resonance. This echo can be seen for 2τ exceeding 1 μs, proving that the actual spin coherence time is at least 100 times that of the originally observed value.

This experiment opens up the real prospect of using the two states, S and T, as a coded qubit, a possibility anticipated and thoroughly analyzed by Levy (*5*) some years ago. He showed that with a fixed magnetic field gradient between the two dots, the SWAP operation alone suffices to execute a quantum computation. The field gradient may itself be produced by differential Overhauser fields obtainable in these kinds of experiment (*6*, *7*). Again, there is a $\sqrt{N}$ fluctuation of these fields; but given the slowness of these fluctuations, there are more magnetic resonance tricks, like the spin echo, for using sequences of SWAPs to erase the effects of these fluctuations.

The remarkable thing about this experiment is that it can make use of all the tricks for reliable operations that are available in magnetic resonance, even though the controls are not magnetic at all—SWAP is controlled by a purely electric pulse. Real magnetic resonance manipulations of spins in this system would be orders of magnitude slower, and none of the results observed would have been possible. It appears now a real possibility that all-electrical control of spins in semiconductors may be a practicable route to real quantum computation.

References

1. J. R. Petta *et al.*, *Science* **309**, 2180 (2005); published online 1 September 2005 (10.1126/science.1116955).
2. D. Loss, D. P. DiVincenzo, *Phys. Rev. A* **57**, 120 (1998).
3. G. Burkard *et al.*, *Phys. Rev. B* **60**, 11404 (1999).
4. A. V. Khaetskii, D. Loss, L. Glazman, *Phys. Rev. Lett.* **88**, 186802 (2002).
5. J. Levy, *Phys. Rev. Lett.* **89**, 147902 (2002).
6. A. C. Johnson *et al.*, *Nature* **435**, 925 (2005).
7. F. H. L. Koppens *et al.*, *Science* **309**, 1346(2005).

10.1126/science.1118921

CHEMISTRY

New Gels for Mixing Immiscible Liquids

Philippe Poulin

Synthetic or natural porous media with a single continuous connected pore space are common. These materials are used in research laboratories as supports for catalysts, as well as in filters for automobile engines and coffee makers. But these classical solid porous media cannot be used to separate two different fluids, nor to keep two distinct liquids in contact for later separation. To achieve these aims, one needs a bicontinuous structure with two continuous media that are intimately combined but separated by porous walls. Such a novel compartmented structure could be of great interest for liquid purification and cleaning, for accurately enriching a liquid with another component dissolved in another liquid, for controlling chemical reactions between immiscible fluids, and for sorting the reaction products afterward. On page 2198 of this issue, Stratford *et al.* at the University of Edinburgh (*1*) report computer simulations of just such a material.

An ideal bicontinuous structure would be made of a rigid self-supporting scaffold with open and continuous walls so that gases, liquids, living cells, biomolecules, or particles can travel through the open spaces. But how can we make such a structure? Bicontinuous liquid phases do exist at thermal equilibrium (*2*). Some oil and water combinations can indeed form bicontinuous phases in the presence of surfactants in well-defined temperature and concentration ranges. Unfortunately, the intrinsic liquid nature and thermodynamically determined structures of these mixtures make the use of such phases for separation or filtration impossible.

Designing materials beyond thermal equilibrium could be a far more versatile way to create a variety of structures. For example, it has been shown that phase separations of fluids (*3*, *4*) can be used to create various structures including gels, droplets, and cellular systems. Fluid demixing thus seems to be an interesting approach to achieve complex morphologies. Consider a mixture of two fluids that are miscible at high temperature. By quenching the system at low temperature, the two fluids undergo phase separation. If the fractions of the two fluids are nearly equal, a bicontinuous structure forms. In the initial stages of the phase separation, the characteristic size (that is, the typical size of the separating domains) of the system is very small. It grows over time until a macroscopic phase separation occurs. If we perform such a simple experiment, we see a bicontinuous structure that spontaneously evolves with time.

At some point, when our ideal imaginary system reaches a characteristic size that would suit the bicontinuous material, we would like to stop the process and solidify the system right away. Unfortunately, the liquid system will just continue coarsening, driven by the unavoidable minimization of energy. Indeed, the growth of the characteristic size of the bicontinuous structure minimizes the amount of interface area between the two separating liquids. Because this interface costs a lot of energy, the characteristic size of the system keeps increasing. Stratford *et al.* (*1*) have proposed a very elegant approach to stop the coarsening at will. In numerical simulations, they have accomplished this by adding small particles that remain trapped at the interface between the two demixing

The author is at the Centre de Recherche Paul Pascal, CNRS, Avenue Schweitzer, Pessac 33600, France. E-mail: poulin@crpp-bordeaux.cnrs.fr