formed; excess RA can reprogram a "distal" amputation blastema (the site of progenitors for regeneration) to produce more proximal in addition to distal structures (*9*). Signaling by WNT and FGF plays an essential role in appendage regeneration in several different systems (*10*, *11*), and WNTs may prolong regeneration in species that normally lose this capacity at metamorphosis (*10*). Whether this occurs through the maintenance of progenitors by WNT and FGF, as seen in the chick limb bud, remains to be seen. The finding that embryonic limb progenitor cells can be manipulated to maintain or extend their plasticity opens a new door to analyzing how these progenitors become committed to particular fates, whether and to what extent this process can be reversed, and the degree to which such programming is shared between limb development and regeneration.

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PHYSICS

A Logical Use for Atoms

The coupled spins of individual atoms can be used to demonstrate basic logic function.

Andreas Heinrich and Sebastian Loth

It is increasingly more difficult and costly to continue to shrink silicon chip components. Moore's law, which describes such progress, is running into serious trouble. Technologists have been seeking out alternative architectures for computation. Some have even pondered the possibility of shrinking the components to the ultimate end of any roadmap—to the scale of atoms. On page 1062 of this issue, Khajetoorians *et al*. present such a radical leap forward (*1*) by demonstrating spin-based logic operation in chains of magnetic atoms on a surface.

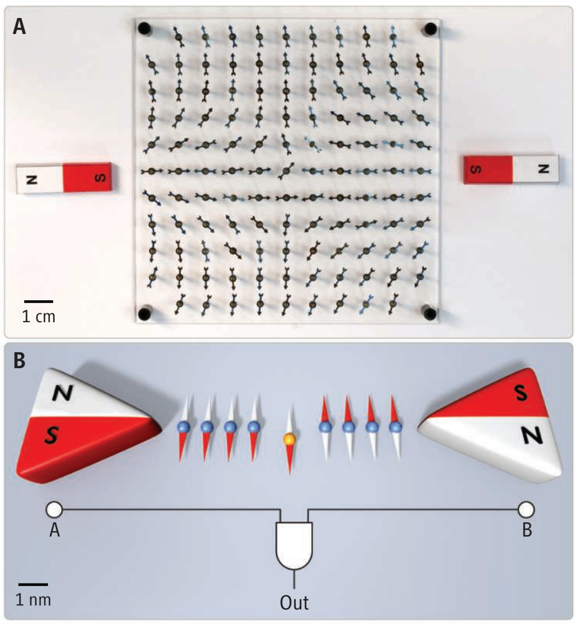
Spintronics promises to add functionality to semiconductor devices by making use of the spin—the magnetic degree of freedom—of electrons that are flowing through devices. But can logic operations be performed without pushing electrons (spin-polarized or not) through wires? Indeed, several schemes have been proposed to do just that. One example is magnetic domain wall logic (*2*). Another relies on the dipolar coupling between magnetic nanodots. Cascades of such dots can meet at intersections where it was shown that logic operations could be performed (*3*, *4*).

About 10 years ago (*5*), it was shown that computation of an arbitrary logic operation on the scale of atoms is possible by using the controlled motion of molecules on a surface. In practice, however, that scheme made the scanning tunneling microscope (STM) an integral part of the logic circuit because repeated operation required precise reassembly of the nanostructure.

In what constitutes a major breakthrough, Khajetoorians *et al*. demonstrate repeatable atomic-scale logic operations with spins of individual atoms. The spin of atoms can be likened to compass needles. Compass needles can in principle carry information from permanent bar magnets (the inputs) to an interaction region (see the figure, panel A). Khajetoorians *et al*. took the bold step of implementing such functionality on a length scale that is seven orders of magnitude smaller. Magnetic atoms were placed on a metallic surface and positioned in precisely defined locations by atom manipulation (*6*). They then used a spin-polarized STM to read the magnetic state of each atom. Relatively large magnetic islands were used as inputs, and chains of magnetic atoms were then coupled to these input bits with a magnetic exchange interaction. In this fashion, the magnetic state of the input island could be transferred to the end of such a chain. Later, a second chain was attached to another input island and both chains were assembled to meet at a central point: the gate, where logic operations were demonstrated.

Khajetoorians *et al*. were able to use an external magnetic field to controllably switch the magnetic state of the input islands independently, by selecting islands of different sizes and hence different switching fields. In their setup, the presence of the STM tip is not required for the gate operation, only for readout of the output state. In essence, they were able to park the STM tip at the output of the gate, switch the state of the two input islands through the four distinct combinations, and watch the output of the logic gate. For certain input configurations (such as the one shown in the figure, panel B), the output of the gate is in a frustrated magnetic state; that is, it is equally likely to point up or down. Khajetoorians *et al*. broke this frustration with a small biasing magnetic field, which allowed them to switch the type of the spin gate from AND to OR. This is a beautiful demonstration of the power of atomically precise manipulation applied to spin systems on surfaces.

These features—independently controllable inputs, signal propagation from one



Shrinking logic. (**A**) An array of compass needles responding to the magnetic field of two bar magnets. (**B**) Coupled magnetic atoms performing a logic operation. Nearest-neighbor exchange interactions transfer the magnetic state of the input islands to the center atom. An equivalent logic circuit with inputs A and B is sketched below.

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point to another, and gate operation with threshold behavior—constitute most of the components needed to enable arbitrary binary logic. So what is preventing the wiring up of an atomic-scale calculator? Aside from practical issues such as room-temperature operation, a conceptual challenge is the implementation of energy gain: Does the binary signal decay in longer chains? Can the output of the logic gate drive one or more successive gates? It is likely that in order to achieve this goal, energy must be put into the system at certain stages. Borrowing ideas from nanodot logic, one possibility might be to elevate the spins into metastable states at a clock frequency (*3*, *4*). If a successful technology could be built from such spins, it promises low energy consumption.

So when will we reach the end of Moore's law? It is clear that the ultimate size limit is the scale of atoms, and this work takes a decisive step toward a real demonstration of spin-based computation at this limit. Given that there is currently about a factor of 1000 difference in areal density between silicon chip technology and the demonstration by Khajetoorians *et al*., there is still sufficient time to tackle the intriguing questions opened up by this work.

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PHYSICS

Chameleon Magnets

An external voltage can switch ferromagnetism on and off in a material at room temperature, which may add new functionality to electronics.

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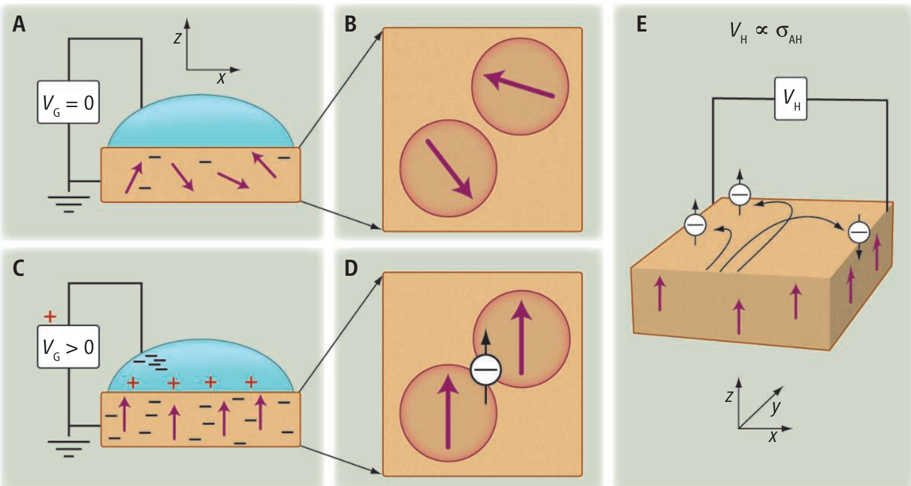
The spin of an electron can serve as a magnetic messenger. Permanent magnetism, or ferromagnetism, comes from the spontaneous alignment of the electron spins and their associated magnetic moments in metals such as iron and cobalt, which results in their or magnetization. Ferromagnetism plays an important role in information storage, not only to keep refrigerator magnets in place (and notes held by them) but to store data in computer hard drives (*1*, *2*). A more common effect is paramagnetism—a material becomes magnetic only when an external magnetic field causes its spins to align. Silicon is paramagnetic, but its semiconductor properties, not its magnetism, make silicon useful in logic circuits. On page 1065 of this issue, Yamada *et al*. (*3*) report a breakthrough that brings together these two different worlds of ferromagnetic metals and paramagnetic semiconductors and may better integrate logic and memory. By adding cobalt impurities to nonmetallic and nonmagnetic titanium dioxide, they created an intriguing material $(Ti,Co)O_2$, which, like a chameleon, can reversibly transform from a paramagnet to a ferromagnet at room temperature.

Electrically controlled material properties are at the heart of modern microelectronics, which rely on devices such as silicon field-effect transistors (FETs). An applied electric field changes the number of current carriers in a semiconductor (an effect called doping) and can switch the current flowing through the FET on and off. This reversible effect differs from chemical doping (adding impurities), where the number of charge carriers is permanently changed. The FET approach allows an electric field to dope the same sample reversibly and even transform it from insulating to metallic (*4*, *5*). Yamada *et al*. start with chemical doping. They replace approximately 10% of Ti^{4+} ions in TiO_2 with Co^{2+} ions, which introduces three aligned spins for each Co^{2+}. The Co^{2+} ions and their spins (depicted by thick arrows in the figure) are localized, and their random orientations do not align in any particular way from Co^{2+} ion to Co^{2+} ion, a characteristic of a paramagnet (see the figure, panels A and B).

With applied positive voltage (depicted in the figure, panel C), extra electrons and their associated spins are added to $(Ti,Co)O_2$. These electrons are mobile and convey information about electron spin alignment between different Co^{2+} ions. The Co^{2+} ions adopt a ferromagnetic alignment and also transfer this spin alignment to the mobile electrons (see the figure, panel D).



Tunable ferromagnetism. Cobalt-doped titanium dioxide, $(Ti,Co)O_2$, is paramagnetic. Yamada *et al*. show that applying a voltage to this material in an electrolytic cell causes it to become a ferromagnet. (**A** and **B**) With no applied gate voltage V_G between the electrolytic top contact and the $(Ti,Co)O_2$, the carrier density (electrons, e^-) is low, and the Co^{2+} spins (violet arrows) interact weakly and are not aligned. (**C** and **D**) For V_G at 3.8 V, the carrier density increases by nearly a factor of 10 and the electrons act as magnetic messengers, aligning the Co^{2+} spins. (**E**) Magnetization can be detected because it creates an imbalance in the electron spin populations. For an electron current flowing in the *y* direction, the spin-up electrons will tend to scatter to the left (–*x* direction) and the spin-down electrons to the right (+*x* direction). With more spin-up electrons, there will be a net accumulation of electrons on the left side of the sample, which in turn can be measured as an anomalous Hall voltage V_H or Hall conductivity σ_{AH}. Reversing V_G to zero transforms the ferromagnet back into a paramagnet.

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